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THE BEHAVIOUR OF VARIOUS ENGINE AND GEAR LUBRICANTS IN SEIZURE TESTS.* †

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Synopsis.

The results described in this paper are part of an investigation of the effect of various lubricants on the seizure characteristics of hard steel in the four-ball apparatus. It is found that ordinary lubricants, as well as extreme-pressure lubricants, give significant results. Commercial engine oils cover a range of quality from similarity with B.P. paraffin almost to fatty oils, overlapping with the mineral gear oils. Two kinds of extreme-pressure lubricants have been tested, early ones of the sulphurized-fatty oil type and more recent ones of the lead soap–sulphur type. The former behave in a similar manner to the mineral and fatty oils, but with appropriately superior qualities. The latter are different, giving appreciable wear at the low loads, and slight rises of friction at moderate loads instead of a sudden rise to a high value at high loads; moreover, they take an enormously high load without welding occurring. Tests have been made of the effect on a mineral oil of the proportion of an extreme-pressure dope of the sulphurized-fatty oil kind, and it has been found that a range of qualities could be obtained.

Kerosine and petrol, although causing appreciable wear even at low loads, behave surprisingly moderately throughout, the damage when "scuffing" occurs being less than with most mineral oils. Finally there is some discussion of the applicability of the results to gear lubrication.

Introduction.

The four-ball apparatus, which has been used in these tests, was originally obtained for tests on extreme-pressure lubricants. On testing ordinary lubricants, however, the results were found to be equally interesting, and the range of substances has therefore been considerably increased. The primary aim in this extension of the work has been to provide information on the nature of wear and seizure. The apparatus has advantages for this work, in that it uses test-pieces (steel balls) which are highly consistent in material and finish, and that it provides well-defined contacts. Moreover, there is apparently freedom from fluid pressure film, which is a considerable advantage, as there is usually difficulty in eliminating the influence of fluid films in test machines.

A secondary aim has been to make a fairly complete investigation with this apparatus, so that comparisons will be possible with the behaviour of the same or similar lubricants in other testing machines, such comparison being a matter of some urgency at the present time.

Earlier work was reported in two papers to the 1937 General Discussion on Lubrication and Lubricants held by the Institution of Mechanical Engineers.[1 2] Where relevant, brief summaries of some of these results are included in the present paper, to make the account of the behaviour of engine and gear lubricants more complete.

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Apparatus and Method of Test.

In this apparatus, supplied by the N. V. de Bataafsche Petroleum Maatschappij, and first described by Boerlage,[3] a ½-inch-diameter hard-steel ball is rotated under load in the cavity formed between three other similar balls clamped together in a cup containing the lubricant to be tested. Means are provided for recording the frictional torque on the balls in the cup, a friction–time chart being produced. Having applied the particular load, the short-circuit driving motor for the top ball is switched on, reaching its running speed of 1500 r.p.m. very quickly. There is a small peak on the friction chart due to the initial movement of the cup and the plate on which it stands. The friction then remains constant until, if the load is high enough, seizure occurs with a rise of the friction to a high value (generally 0·3–0·55); normally there is recovery from the seizure, the friction falling to a steady value. The motor is switched off after 1 minute.

Impressions closely circular in shape are worn on the three clamped balls. If seizure does not occur, the diameters of these impressions are closely equal to those calculated by Hertz's formula for elastic deformation under static loading. The mean diameters are plotted against the loads on logarithmic paper, and the Hertzian values plot as a straight line (cf. Fig. 2). When seizure occurs, the impressions are much larger, and the points fall generally on a straight line above the Hertz line. The load at and above which seizure occurs in the course of the one-minute run is referred to as the breakdown load; it is thus given by the line joining the two portions of the wear-load curve. If the load is made high enough, the seizure ultimately becomes so severe that the balls weld together. The time to seizure decreases with increase of the load, at a decreasing rate (cf. Fig. 2). There is normally some " scatter " of the plotted observations, as is to be expected from the consideration that, when failure is imminent, the roughness of even bearing-ball surfaces must be large compared with the thickness of the boundary oil film; the failure will thus depend on the particular configuration of the contact surfaces, which is certain to vary somewhat from test to test with different balls.

As regards the initial specific pressures, it may be noted that when the load (on the single ball) is 20 kg., the maximum pressure at the centre of each contact area, calculated according to the Hertz theory, is 27,600 kg./cm.^{2} (175 tons/in.^{2}); when the load is 100 kg., the maximum pressure is 47,100 kg./cm.^{2} (300 tons/in.^{2}). The mean pressure over the contact area is two-thirds of the maximum. The linear speed of translation is 58 cm./sec. (113 ft./min.).

The balls were all of one make, and no difference has been found between different consignments that was greater than the variation in the results with any one consignment. The results were not dependent on the particular method of initial cleaning with solvents.

Early Extreme-Pressure Lubricants.

The extreme-pressure lubricants previously tested [1] were current types in November 1935, and consisted of sulphurized fatty oil in mineral oil, except in one case, where a chlorinated compound was used. The mean

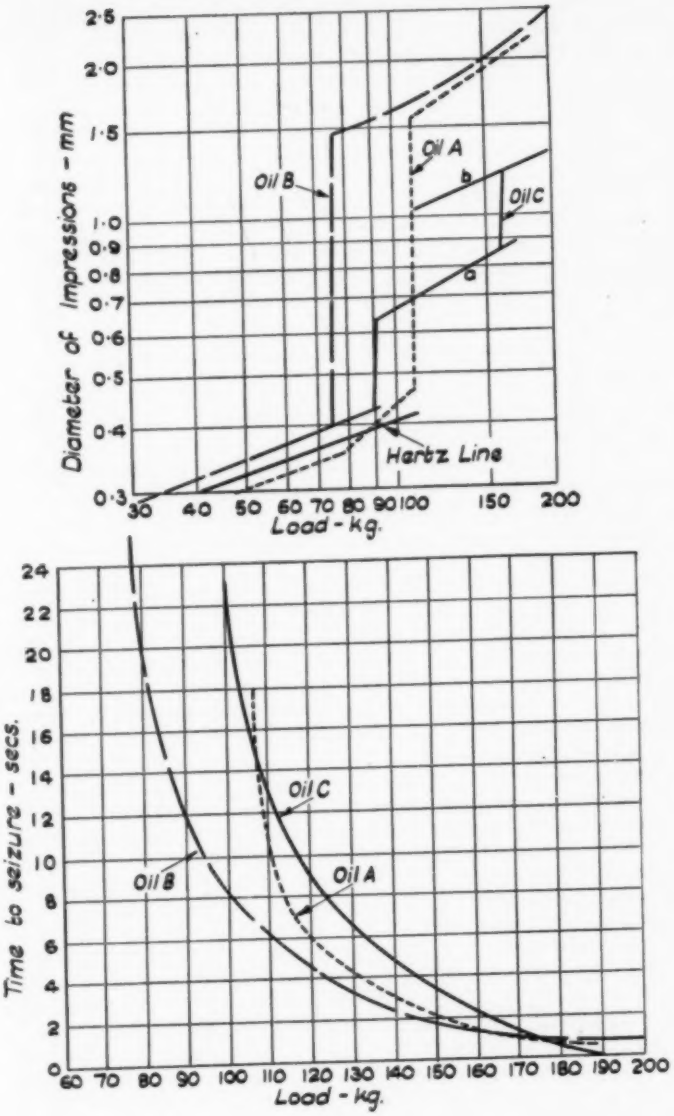


FIG. 1.

EARLY-TYPE EXTREME-PRESSURE LUBRICANTS.

wear and seizing-time curves are shown in Fig. 1. Oil A represented three oils very similar to each other (including the one containing the chlorinated compound), and oil B was generally similar, but had a rather lower breakdown load. Oil C was different in giving two types of seizure, and wear impressions in two corresponding groups. In the one case with this oil only a slight rise of friction occurred, the friction falling again slowly; the wear was moderate (region *a* of Fig. 1). In the other case there was a sharp peak in the friction–time chart and a quick recovery; the wear was then higher (region *b* of Fig. 1). The maximum coefficient of friction at seizure was 0·4–0·5 for oil B and those represented by oil A, but was 0·2–0·35 for oil C when a peak was obtained and 0·15 otherwise. The time to recovery was generally 1–1½ seconds, but rather more than 2 seconds for oil B.

The Effect of the Proportion of a Dope.

After completing the work just described, a small quantity of extreme-pressure dope (marketed in January 1937) became available, and in view of the interest at the time in adding small quantities of dope to oils to improve their oiliness, some tests were made on the effect of adding different proportions to a mineral oil. The makers gave the information that the dope was prepared by adding 10 per cent. of sulphur chloride to a mixture of equal parts of mineral and fatty oil, and then expelling hydrochloric acid and chlorine.

The mineral base oil chosen was a current, winter-grade, motor-car engine oil. The seizing-time and wear-load diagrams for this base oil, H1, and for the mixtures containing 1·27 per cent. and 0·15 per cent. of dope, are shown in Fig. 2. (In the seizing-time diagram the arrows at the top indicate that in these tests there was no seizure within the 60 seconds of the test; where a number is added, this shows the number of seconds to seizure, the point falling above the limit of the diagram.) It was interesting to find that the 1·27 per cent. mixture showed peculiar characteristics similar to those of the oil C referred to above. As with this oil, two types of friction–time charts were obtained, as shown at (*a*) and (*b*) in Fig. 3. In chart (*a*) the friction rose relatively slowly to the maximum, and then only slowly decreased in value during the remainder of the one-minute run, there being no recovery of the usual kind. In chart (*b*) there was a sharp rise to maximum friction and a quick recovery; this was the type of chart obtained uniformly with all the normal extreme-pressure lubricants previously tested. Further, for the same load, the first type of seizure occurred only after a relatively long time, and both the maximum coefficient of friction at seizure and the wear were less than when the second type of seizure occurred. In the seizing-time-load diagram in Fig. 2 the long times are uniformly those of the first type of seizure; the corresponding wear values are plotted in region *a* of the wear-load diagram. The values of the maximum coefficient of friction at seizure were all about 0·3, whilst those with the second type of seizure ranged from 0·45 to over 0·6 with increasing load. The wear values corresponding to the latter are plotted in region *b* of the wear-load diagram; this wear was closely equal to that of the normal extreme-pressure lubricants at the corresponding loads.

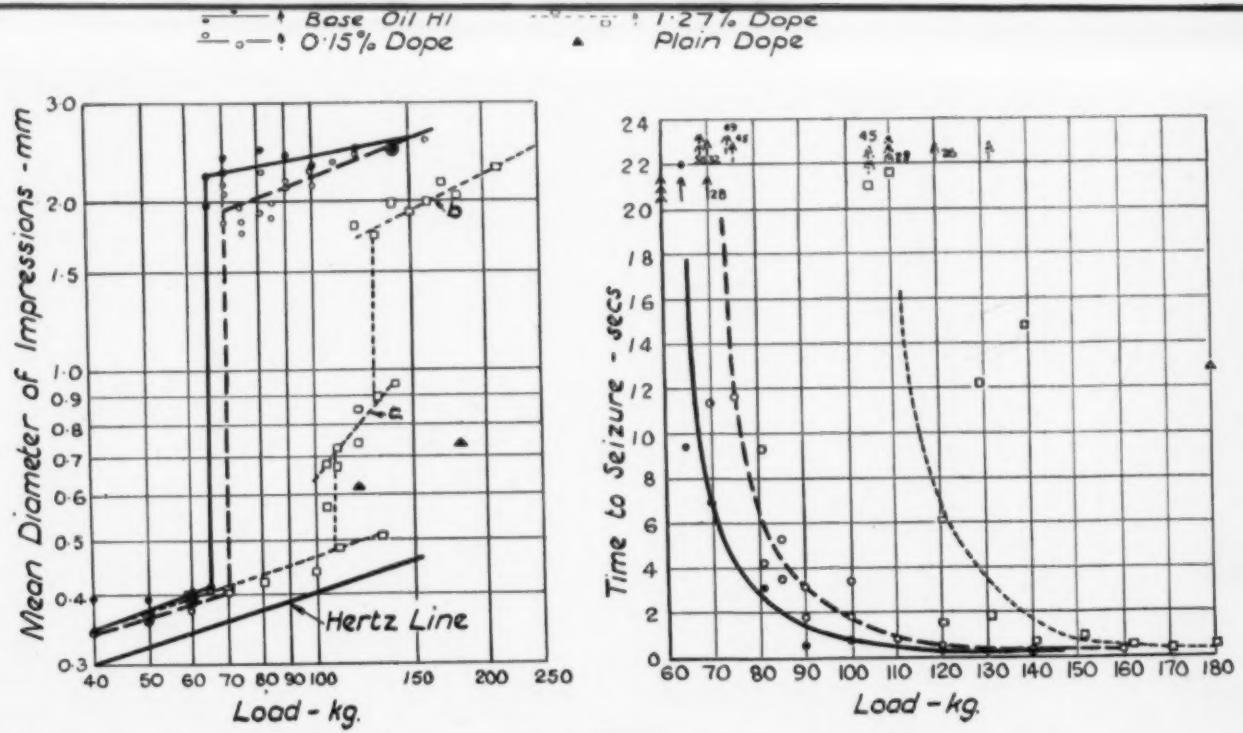


FIG. 2.

DOPED MINERAL OIL.

It may be noted that whereas the breakdown load to mild seizure was about 110 kg. (as high as the best of the extreme-pressure lubricants), the fact that the times to seizure were so long would add to the safety in many mechanisms, the extra time giving opportunity for conditions to change.

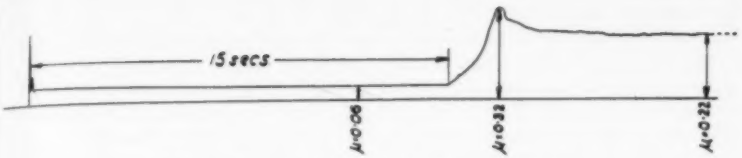
At 170 and 210 kg. there was quite exceptional behaviour with this mixture: after recovery in the normal way the coefficient of friction gradually and smoothly rose again to about 0·3, and remained at this or a slightly lower value until the end of the test. The effect on the size of the wear impressions was apparently not very great. This behaviour had never been found in any of the previous very large number of tests.

The 0·15 per cent. mixture behaved consistently throughout. The effect on the base oil was much less than with the 1·27 per cent. addition, but was beneficial in all respects. The breakdown load was 5 kg. higher, the times to seizure were greater, and the wear was rather less at the lower loads at which seizure occurred. The time to recovery from seizure ranged from 3 to 7 seconds, averaging 4½ seconds, compared with 7 to 12 seconds, with an average of 9½ seconds, for the base oil. The maximum coefficient of friction at seizure ranged from 0·45 to nearly 0·6 in each case. Typical friction–time charts are shown at (*c*) and (*d*) in Fig. 3. There were black deposits in the impressions with the doped oil; this points to decomposition having occurred at the high temperatures reached at the contacts.

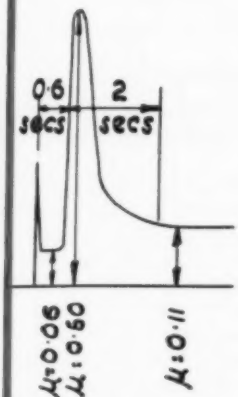
It is interesting to note how this 0·15 per cent. mixture compares with castor oil[2] (see p. 720). The breakdown load is only 5 kg. lower, and the time to seizure is a little less; the wear with seizure, however, is on the average the same over the range of loads, but is different in that the slope of the mean curve for this portion of the wear-load diagram is less than for castor oil. Further, a welding seizure was obtained with castor oil at 150 kg., whereas the behaviour with the doped oil was normal at 160 kg. The time to recovery averaged 4½ seconds, compared with 3 seconds for castor oil. Generally the results are very similar to those for rape oil as previously reported,[2] although here again a welding seizure occurred at 150 kg. It seems, therefore, that properties similar to those of fatty oils might be conferred on a mineral oil by the addition of a small proportion of dope such as the one being tested, and if welding seizure with fatty oil is due to major decomposition, as is not unlikely, it is possible that the stability of the mineral-oil mixture might extend the range of application of such oils.

Tests were made of the plain dope itself at 120 and 180 kg. At the lower load no definite seizure occurred, but there was some irregularity of the friction–time chart; the position of the plotted point in Fig. 2 shows that this irregularity was associated with some wear. At 180 kg. there was a seizure after 13 seconds, but the friction rose from the basic 0·05 to only 0·10, recovery occurring in 6 seconds; the wear was relatively small. The dope itself was therefore not characterized by high breakdown load, but by features related with the friction; the low wear was associated with low friction and quick recovery. The dope attacked the balls and cup, blackening them in the period of the test.

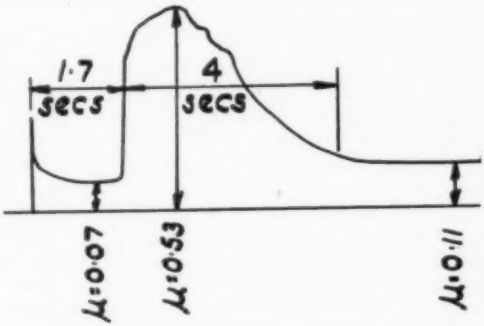
Tests of mixtures containing 0·02 per cent. and 0·005 per cent. of dope were of interest in seeing how small a proportion of dope would affect the



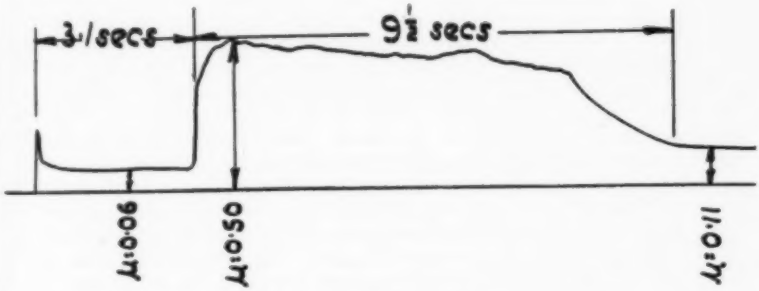
(*a*) Mineral Oil H1 + 1·27% E.P. Dope. 140 kg.



(*b*) Mineral Oil H1 + 1·27% E.P. Dope. 140 kg.



(*c*) Mineral Oil H1 + 0·15% E.P. Dope. 100 kg.



(*d*) Mineral Oil H1. 81 kg.

FIG. 3.
FRICTION–TIME CHARTS.

behaviour of the base oil, in view of the possible use for "oiliness" improvement. With 0·02 per cent. of dope the breakdown load was 70 kg., as with 0·15 per cent., and a certain number of long times to seizure were obtained, raising the mean seizing-time-load curve to almost the same position as that of the 0·15 per cent. mixture. In other respects, however, the difference from the base oil was only just perceptible; thus the wear with seizure at the lower loads was rather less in a number of cases, and the time to recovery ranged from 5 to 11 seconds, with an average of 8 seconds, just a little less than for the base oil. With another mineral oil of much inferior quality, 0·02 per cent. of this dope increased the breakdown load by nearly 10 kg., but otherwise was without effect. With 0·005 per cent. of dope the results were identical with those of the base oil.

Recent Extreme-Pressure Lubricants.

Results are now given for more recent commercial types of extreme-pressure lubricants (purchased early 1938), which showed marked differences from the earlier ones.

The first of these, E, was a medium-viscosity hypoid gear oil of the lead soap–sulphur type (10 per cent. lead naphthenates, and 2¼ per cent. sulphur). The seizing-time and wear diagrams are plotted in Figs. 4*a* and 4*b*, and the mean curves of a typical extreme-pressure lubricant D of the earlier type are superimposed on the diagrams to show the differences. Instead of the breakdown at a certain load and a sudden increase of diameter of impression, the later lubricant E gave a gradual increase of diameter throughout the whole range of loads. From 20 to 50 kg., region *a* of Fig. 4*b*, the impressions were similar to the non-seizure type of previous tests—viz. flat, very lightly scored impressions—but the diameters were rather greater, as can be seen from the positions relative to the Hertz line. A photograph of a typical impression of this type is shown at (*a*) in Fig. 5. From 50 to 70 kg., region *b* of Fig. 4*b*, the impressions became slightly cupped instead of flat, although still remaining round, as shown at (*b*) in Fig. 5; however, this further removal of material in developing the cupped form was not accompanied by any variation of friction sufficient to show on the charts. The size of the impressions was higher still than for the earlier type of lubricant D. From 80 to 150 kg., region *c* of Fig. 4*b*, an action more like tearing of the metal occurred, the impressions being rough and the edges irregular. The impressions were no longer round, and examination of a number of balls suggested that relatively large particles were torn out of the contact region, and, being carried round by the top ball, caused scoring of the ball surfaces outside the initial contact area by being trapped in the space between them; the impressions were thus elongated at right angles to the direction of motion, as shown at (*c*) in Fig. 5, in which the original circular impression can be seen faintly. This tearing of the metal was accompanied, from 90 to 150 kg., by very slight changes of friction, the maximum coefficient being only 0·11 in all cases. The "times to seizure" in Fig. 4*a* are the times to this rise of friction, as representing the first stage of failure, but it is important to contrast this mild behaviour with that of the earlier type of lubricant, with which the coefficient of friction rose at failure for a short time to a peak value of

over 0·4 at corresponding loads. Fig. 4*a* shows that the times to the change of friction are shorter, indicating inferiority; on the other hand, the wear does not rise at corresponding failure loads to the high values of the earlier type of lubricant. Similarly the load at which this curve becomes vertical is not a breakdown load in the usual sense.

There is thus a need for an explanation of the mechanism of the action of the lubricant, by which with the one type there is a gradual transition with increase of load from a fine wear (with removal of particles ranging

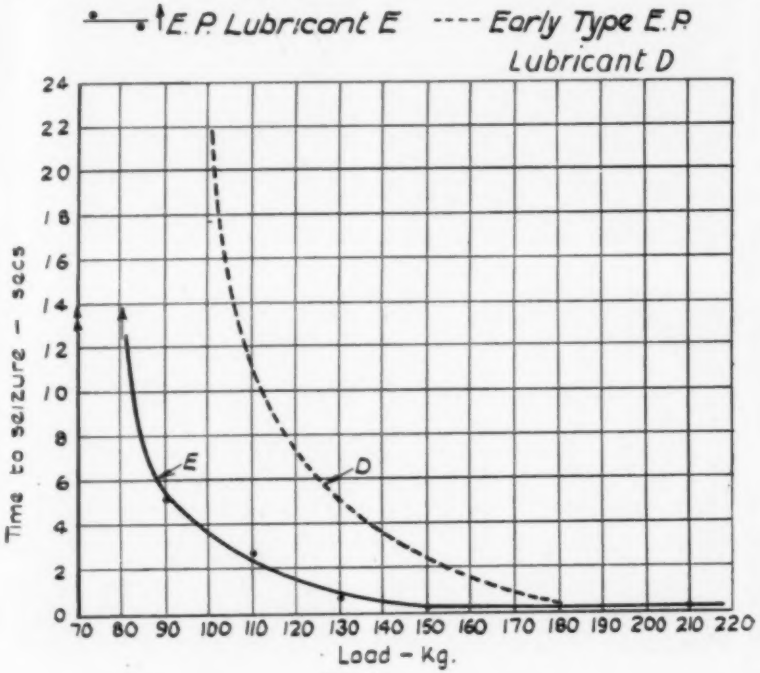


FIG. 4*a*.

TWO EXTREME-PRESSURE LUBRICANTS.

possibly from the crystal size of hard steel to even molecular size) to a tearing wear (in which particles consisting of groups of crystals are removed), and with the other a finer wear persists to a relatively high load, but then there is a sudden removal of large particles, to a greater extent than occurs in the former case. The coefficients of friction before seizure occurred were not dissimilar in the two cases, so that explanation on the basis of the heat developed is not feasible.

Although the time to "seizure" had become so short at 150 kg., the wear was so moderate that tests were made at higher loads to see what would happen. It was found that the load could be taken to the limit of the machine (730 kg.) without very great alteration in the character of

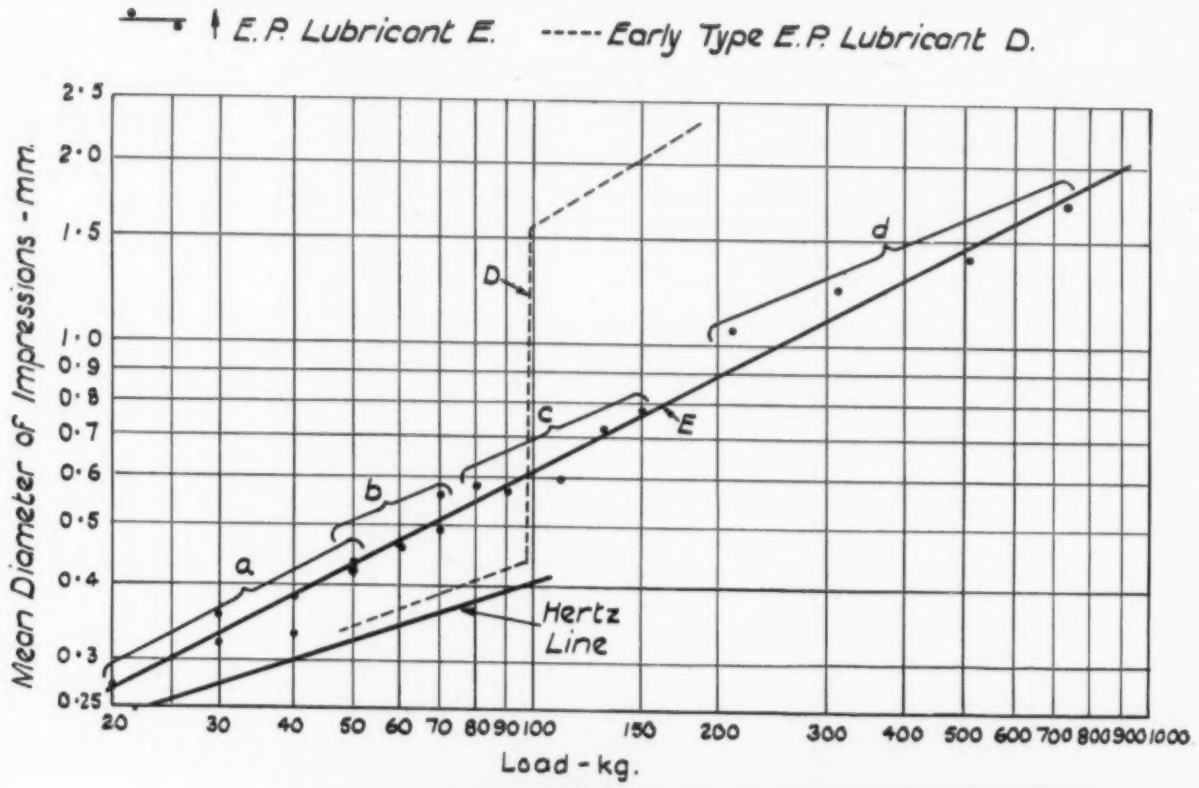


FIG. 4b.

TWO EXTREME-PRESSURE LUBRICANTS.

(C) (A)

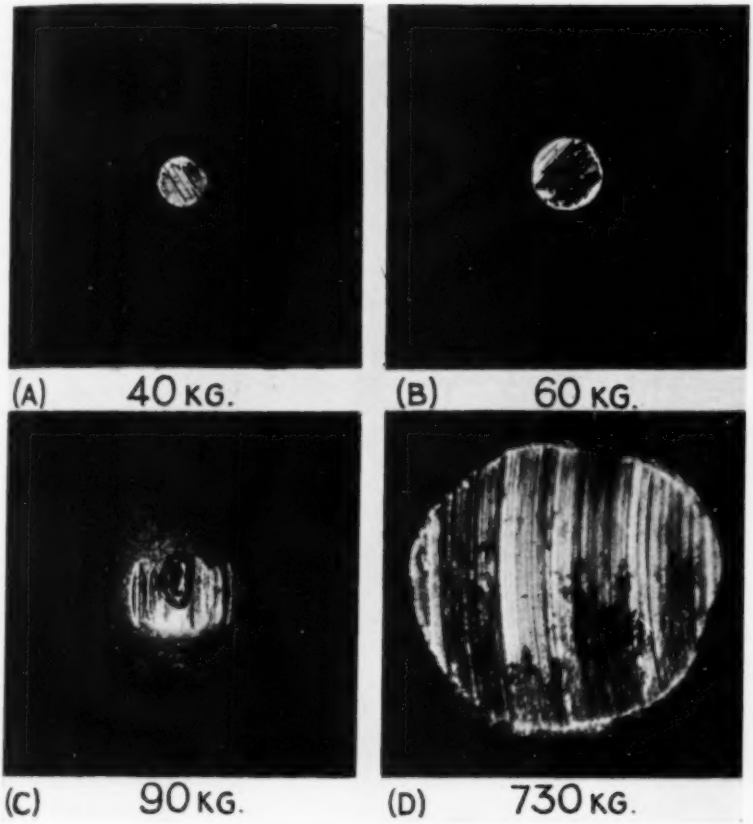


FIG. 5.

WEAR IMPRESSIONS ON STEEL BALLS WITH EXTREME-PRESSURE LUBRICANT E.

(Magnification = 25 ×.)

[*To face p.* 718.

FIG. 4b.

TWO EXTREME-PRESSURE LUBRICANTS.

FIG. 8.

WEAR IMPRESSIONS.

the failure. The impressions were progressively larger and were rounder, becoming cupped as in a seizure with other lubricants, but the size at the highest load was still no larger than those of the earlier lubricant at 100–150 kg., see region *d* of Fig. 4*b*. A photograph of the impression at 730 kg. is shown at (*d*) in Fig. 5.

At 210 kg. and higher loads a thick black deposit was formed round each of the impressions, and in considerable quantity on the top ball, presumably due to decomposition of the lubricant at the high temperatures reached at and near the contacts. Smaller amounts of staining had occurred at lower loads, down to 130 kg., but the amount of deposit became much greater at 210 kg. and above.

At these higher loads failure occurred immediately the test began and the maximum value of the coefficient of friction could not be ascertained with any accuracy; the earliest value that could be measured was quite low, however, being about 0·13, and falling smoothly to about 0·07. The earlier type of extreme-pressure lubricant with which the present one is being compared was not tested beyond 180 kg., but with another of the same type there was a complete failure at 210 and 250 kg., the balls welding solidly together with the material melted or softened at the contacts (compare Fig. 8(*b*)).

Considering the wear results as a whole, all the points fall fairly closely on a straight line, the deviations of the points at each stage not justifying any departure from this form. At low loads the lubricant must be considered to be inferior to most of the lubricants of all kinds previously tested, in that greater wear occurred during the test. When the breakdown load of those lubricants is passed, however, this one is greatly superior, in that the coefficient of friction and the wear were smaller, and an enormously high load could be taken without catastrophy. In use, therefore, it would appear that a low continuous wear would have to be tolerated for the sake of immunity from severe failure when high loads were encountered.

Two other extreme-pressure lubricants, F and G, sold by one company, were tested. Oil G was specifically a hypoid gear lubricant, containing 4½ per cent. lead soap and 2½ per cent. sulphur, whilst oil F was a milder, general-purpose, extreme-pressure lubricant, containing 13½ per cent. fatty oil, 1½ per cent. sulphur and 10 per cent. chlorinated product (3 per cent. chlorine). Oil G was thus of similar type to oil E described above, but contained less lead soap; oil F apparently differed from the earlier lubricants of the sulphurized fatty oil type in containing a chlorinated product in addition.

This chlorinated product altered the whole character of the behaviour of the lubricant. Comparing the wear curve with that of oil D in Fig. 4*b*, the definite breakdown no longer appeared, and loads up to the limit of the machine could be taken without a welding seizure occurring. The wear diameter increased continuously with load, the plotted points falling on a straight line as in the case of the lead soap–sulphur lubricant E described above. Indeed, there was a very close similarity in behaviour in all respects to this lubricant, closer actually than in the case of the other lead soap–sulphur lubricant G. With the latter there was a difference of behaviour from that of oil E in the region of 150 kg. which resulted in the wear rising locally to almost double the value.

Generally, lubricant G gave more wear than that, F, containing the chlorinated product, except at the highest load, although F was said to be a milder, general-purpose lubricant. The wear results for F and the lead soap–sulphur lubricant E were on the average about the same, but the rate of variation with load was different; the smaller wear for F at the low loads must be counted an important advantage for general use. The times to rising friction showed the increasing order of quality G, E, F; the general-purpose lubricant is thus best, the curve being practically the same as that of the early extreme-pressure lubricant D. Owing to the rise of friction not being as high as with other lubricants, however, these curves cannot be given the significance previously attached to the seizing-time curves, and in particular the load at which the curve becomes vertical cannot be regarded as a breakdown load with quite the same weight as before. Staining round the impressions, presumably due to decomposition of the lubricant, occurred as with lubricant E, increasing from traces at about 100 kg. to noticeable amounts at 210 kg. and higher; that with lubricant F was lighter in colour than with lubricants E and G. Comparing the wear results with those of other substances, the mean wear curve for lubricant G crosses over that for "golden syrup" [2] between 100 and 150 kg., to show greater wear at the higher loads; it similarly passes through the results for the exceptional sulphurized-fatty oil lubricant C, Fig. 1.

Other Gear Lubricants.

Castor Oil.[2]

The breakdown load for castor oil was 75 kg., intermediate between the mean values for the mineral oils and the early extreme-pressure lubricants, although equalling that of the worst (B, Fig. 1) of the latter. A welding seizure was obtained at 150 kg. The maximum coefficient of friction at seizure varied from 0·45 at low loads to nearly 0·6 at the highest. The time to recovery from seizure varied from 3 to 5 seconds, again intermediate between the mineral and extreme-pressure oils.

Oils Containing Zinc Oxide.[1]

Comparing a gear-box oil X and a back-axle oil Y, both containing zinc oxide, with their mineral base oils, the most striking effect of the zinc oxide was the conversion of long, ragged seizures into much smoother, short seizures, almost as good as those of castor oil. The times to recovery were 3–4 seconds for the gear-box oil and 4–7 seconds for the back-axle oil, compared with 20 to over 60 seconds and 20–40 seconds for the base oils, respectively. The wear with seizure was correspondingly reduced, becoming very similar to that of castor oil, and the appearance of the wear impressions was improved, the impressions being smoother and not discoloured by heat. The zinc oxide has no effect on the maximum coefficient of friction at seizure. The breakdown load for the gear-box oil was raised some 10 kg. to that of castor oil, but that of the other was scarcely affected. The wear when seizure did not occur was higher than usual with the gear-box oil, as though the zinc oxide were abrasive, but there was no such effect with the back-axle oil. Testing castor oil containing zinc oxide

there were only the very minor differences from plain castor oil of a few mild seizures in the neighbourhood of the breakdown load, and a slightly lower wear at the highest seizure loads.

Mineral Engine and Gear Oils.

The results for all the engine and gear oils so far tested in this apparatus are collected in Table I, those for B.P. paraffin being added as a matter of interest. Most of these results have been given in earlier papers; the exceptions are H1, described earlier in this paper (p. 712), H2, as ample of nominally the same oil obtained previously, and oil J. This last oil was known to contain an oxidation inhibitor, and this addition was said to improve the behaviour under high-pressure conditions; the results below show, however, that the oil falls rather low in the scale of the mineral oils.

Table I.

Results for Mineral Engine and Gear Oils.

Oil and Reference.	Description of Oil.	Breakdown Load, kg.	Maximum Coefficient of Friction at Seizure.	Time to Recovery, secs.	Average Intensity of Pressure at Breakdown Load, lb./in.².	
					No Seizure.	Seizure.
B.P. Paraffin [3]	Medicinal oil	40	0·3–0·5	20 to >60	286,000	16,600
Oil H2	Winter-grade, motor-car engine oil.	40	0·3–0·5	15 to >60	280,000	16,800
Oil J	Summer-grade, motor-car engine oil.	40	0·3–0·5	20 to >60	247,000	10,200
Dried Oil [3]	Winter-grade, motor-car engine oil.	50	0·3–0·45	15 to >60	290,000	(12,500)
Oil B [3]	Solvent-refined summer grade, motor-car engine oil.	55	0·35–0·5	15 to >60	284,000	10,000
Oil G [1]	Motor-car gear oil.	55	0·35–0·5	20 to 30	276,000	(10,500)
Oil A [3]	Conventionally-refined summer grade, motor-car engine oil.	60	0·4–0·5	5 to 15	332,000	13,000
Base Oil X [1]	Motor-car, gear-box oil.	60–65	0·4–0·55	20 to >60	277,000	9,100
Base Oil Y [1]	Motor-car, back-axle oil.	65	0·4–0·55	20 to 40	316,000	9,300
Oil H1	Winter-grade, motor-car engine oil.	65	0·45–0·55	12 to 7	286,000	9,700
Oil JXB [1]	Partly-refined gear oil.	75	0·45–0·55	3 to 4	317,000	17,300

In Table I the oils are arranged in the order of increasing breakdown load. The range is from 40 to 75 kg., thus overlapping that of the fatty oils, and it is interesting to note that the range for motor-car engine oils is from 40 to 65 kg., indicating marked differences of properties under these test conditions. Most striking is the difference between the two kinds of nominally the same oil, H1 and H2. The inferiority of the solvent-refined oil to the same brand of conventionally-refined oil, oils B and A respectively, may be noted; this is the one known case where this comparison can be made. Two of these motor-car oils have very closely the same properties as medicinal paraffin in this test. The range for the few gear oils tested lies generally a little higher than, but overlaps, that of the engine oils. The gear oil with the highest breakdown load, JXB, is exceptional in being only partly refined and probably containing an unusually large proportion of unsaturated constituents; this oil behaved like a fatty oil in time to recovery and wear, as well as in breakdown

load. That the unsaturated constituents are so effective in this test is interesting. They are expected to be effective in friction tests, but whereas additions of fatty acid to an oil are effective in friction tests, they are not so influential in the high-pressure test, even as much as 10 per cent. of oleic acid in B.P. paraffin having only a very moderate beneficial effect.[2] The difference due to adding 10 per cent. oleic acid is barely as great as that between the conventionally-refined oil A and the solvent-refined oil B. The one gear oil G known to contain a proportion of solvent-refined oil is inferior to engine oil A. Three of the gear oils (all the normal ones) are inferior to the exceptionally good engine oil H1.

Table I shows that with increase of breakdown load there is some increase of the maximum coefficient of friction at seizure. With one or two exceptions, however, there is a general tendency to the same value at the same load; the same values are obtained with the fatty oils castor and rape, and it is apparent that some fundamental phenomenon is occurring. It is thought to be significant that the mean values found, 0·35 at 50 kg., 0·5 at 100 kg., are similar in order to the values found for the coefficient of friction of clean dry steel on steel. The values obtained with the extreme-pressure lubricants are lower, but there may be some chemical action in this case, making the comparison invalid.

With all the oils except H1 the time to recovery increases with load; also, generally the slope of the wear curve beyond breakdown is greater when the time to recovery increases rapidly to high values, the very flat curve for oil H1, for which the time decreased with increase of load, being noticeable. For the range of oils, there is little systematic variation of the time to recovery with breakdown load, except perhaps in the sharp decrease at the highest breakdown loads. In the cases in which there is a smaller average value, there is generally less wear, as would be expected. No definite explanation of the mechanism of the recovery has been found, but there must be a re-establishment of some kind of effective lubrication. The surfaces are sufficiently rough to make the formation of a complete fluid film seem impossible, and there must be at any rate a large proportion of boundary friction. The quality of the oil which leads to quick recovery from seizure is desirable to reduce the amount of damage should failure occur in practice. It is probably of importance in running-in, for when local cohesion occurs at the high points in contact, the removal of material is much more likely to remain local with an oil giving quick recovery. Similar behaviour may be expected with regard to particles trapped between the surfaces. As regards the possible partial influence of this feature on breakdown load, it may be noted that with the different classes of lubricants there is quicker recovery with the lubricants giving the higher breakdown load.

Generally the wear resulting from seizure at the breakdown load increases with increase of this load. Working out the intensities of pressure on the projected area of the impressions, assuming uniform distribution, the values given in the last column of Table I are obtained. In a few cases the mean wear value corresponding to the breakdown load is not well defined, and the calculated pressures are then put in brackets. Over the middle of the range of breakdown loads the pressures are scattered within $\pm$ 2000 lb./in.^{2} of 11,000 lb./in.^{2} (*i.e.*, $\pm$ 20 per cent.), showing a general

tendency to proportionality of load and area. The exceptional values depart so widely from this range, however, as to reduce the significance that might be attached to this result. Moreover, at higher loads than the breakdown loads, at which similar behaviour might be expected, the intensities of pressure not only depart greatly from these values but differ enormously from each other. A fundamental feature is therefore not apparent. For the purpose of comparison with the values given above, it may be added that the intensities of pressure at breakdown load for the fatty oils tested were: castor oil 18,600 lb./in.^{2}, and rape oil (two samples) 11,700 and 14,400 lb./in.^{2}; for the worst (B) of the early extreme-pressure lubricants (Fig. 1) and the normal one (A) the values were 26,000 and 32,800 lb./in.^{2}, respectively.

The mean intensities of pressure when seizure does *not* occur at the breakdown load are given in the next to the last column of Table I. These values take into account the small differences of departure of the size of the impressions from the Hertzian size, and the effect is to destroy any systematic variation with the breakdown load. The average value is 290,000 lb./in.^{2} (130 tons/in.^{2}). If therefore seizure ("scuffing") occurs at this load, the pressure that can be taken is reduced to 1/30 of its no-seizure value.

It is apparent from the above account that whilst the breakdown load is the most important single quantity observed, the other observations all contribute to assessing the qualities of an oil.

Kerosine and Petrol.

Interesting results having been obtained with a variety of lubricants, and the results apparently being independent of viscosity, it was decided to try really thin liquids.

Kerosine.

In tests of kerosine almost immediate seizure occurred at all loads except the lowest load of 20 kg. There was recovery from seizure, however, the time to recovery being very short for low loads; it increased with increase of load from less than 1 second for 30 kg. to 2½ seconds for 60 kg. The maximum coefficient of friction also increased from 0·25 to 0·3 over the same range of loads; the values were thus quite moderate for seizures. A typical friction–time chart is shown at A in Fig. 6. With seizure occurring at all these loads, there was no portion of the wear curve following the Hertz line, as in the case of the ordinary lubricating oils: there was a progressive departure as shown at *a* in Fig. 7, the appearance of the impressions gradually changing from a lightly-scored, flat impression to a scored, cupped impression, in a similar manner to the extreme-pressure lubricants E, F, and G. (pp. 719 and 720). The wear in this region was only slightly greater than with the extreme-pressure lubricant G.

Above 60 kg. the seizure hump in the friction–time chart became much more pronounced, as shown at B in Fig. 6. The time to recovery became generally longer, 4–8 seconds, and the maximum coefficient of friction higher; the latter increased from 0·4 at 65 kg. to 0·5 at 100 kg., thus equalling the average values for mineral and fatty lubricating oils. Corre-

sponding with these increases the wear suddenly became greater, to give portion *b* of the wear curve in Fig. 7 for the range of high loads. The seizure at 120 kg. was so severe that the balls welded together; material was wiped off the top ball into the spaces between the bottom ones. It is interesting to note that the wear in this region of high loads was less than with most of the mineral oils; the appearance of the impressions was similar.

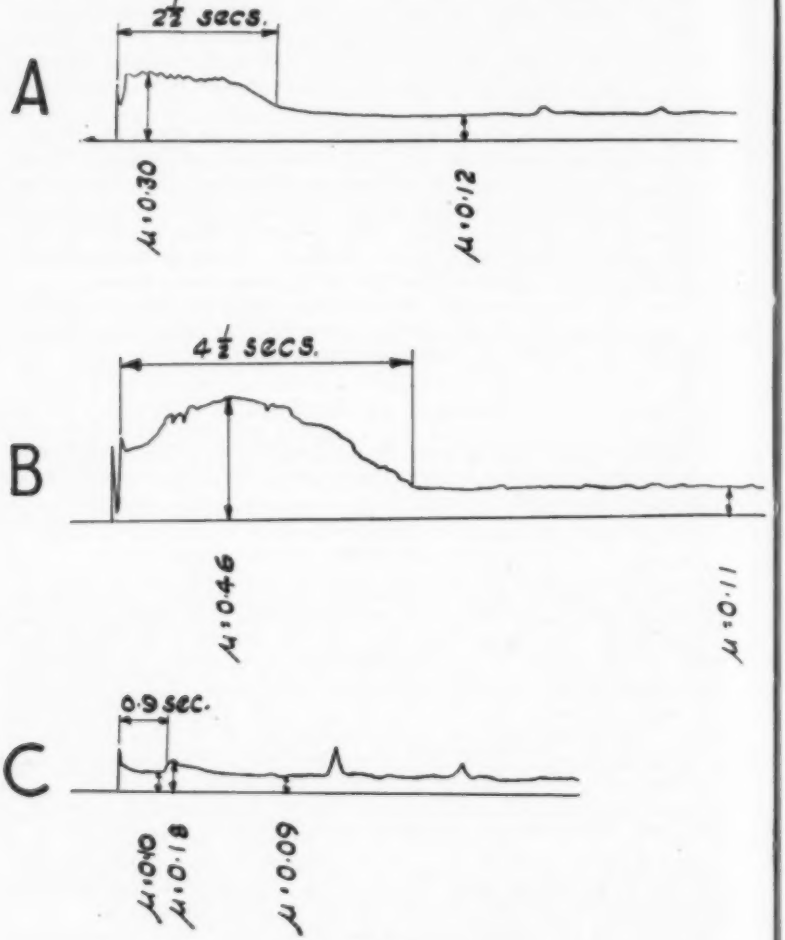
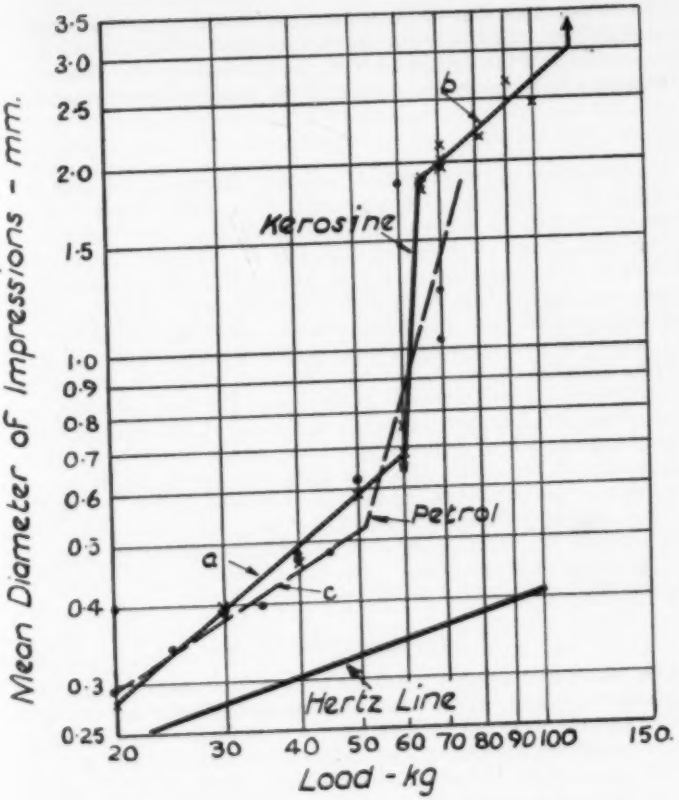


FIG. 6.

FRICTION–TIME CHARTS.

A. Kerosine. 60 kg.
B. Kerosine. 70 kg.
C. Petrol. 45 kg.



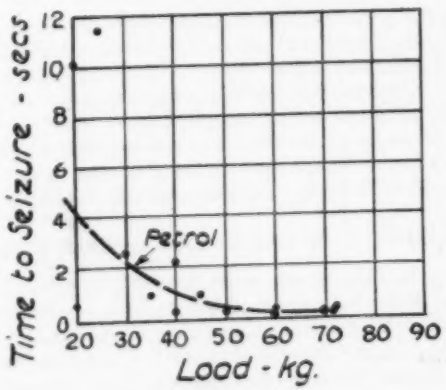


FIG. 7.

KEROSINE AND PETROL.

The friction–time charts were not quite as smooth as usual after recovery, very slight irregularities occurring at intervals, indicating not quite the same stability of lubrication as with the lubricating oils; the coefficient of friction was, however, about equal to the average for mineral oils.

Petrol.

In a number of ways petrol (aviation, hydrocarbon) behaved like kerosine, but generally less consistently. The slight seizure at low loads became with petrol a series of kicks in the friction–time chart decreasing in size with time, as shown at C in Fig. 6. The maximum coefficient of friction averaged about 0·2. At these low loads a regular series of points was obtained for the wear curve in the region *c*, Fig. 7, the wear tending to be rather less than with kerosine. At 60 kg. and higher, however, the behaviour was more uncertain, ranging from seizures with quick recovery, although rather higher friction than before, to seizure without any recovery in the 60 seconds of the test. The heat generated at these higher loads led, however, to boiling of the petrol, and as it seemed likely that the formation of bubbles of vapour at the contacts would lead to uncertainty of behaviour, the tests were not carried on further. There were signs of abnormal heating in some cases, confirming this point.

Thus, although these thin liquids are not regarded as lubricants—in fact generally the reverse—the behaviour is quite moderate, in spite of the high pressures at the contacts. Even when "scuffing" occurred, the wear was less than with most of the mineral oils.

Petrol–Mineral Oil Mixtures.

The effects of the petrol in a 6 per cent. mixture with mineral oil A (see Table I) were only slight. The breakdown load was lowered by about 5 kg., and the wear results with seizure were rather more variable. The latter result was apparently due at the lower seizure loads to a lowering in some cases of the maximum coefficient of friction, and at the higher loads to a prolonging of the time to recovery.

Increasing the petrol content to 30 per cent., the form of the wear curve was still the same, but the breakdown load was a further 5 kg. lower, and the wear was generally rather higher with seizure than with the plain oil. Again, however, the influence of the petrol was seen in a number of milder seizures being obtained, with consequent lower wear.

With both concentrations there was normal wear at loads below 50 kg., corresponding in the usual way with the Hertzian values, and not showing the continuously increasing wear characteristic of the plain petrol.

APPLICABILITY OF THE RESULTS TO GEAR LUBRICATION.

The results in this report were determined primarily as interesting observations of the behaviour of the various lubricants under the particular experimental conditions, covering a portion of the field in which seizure occurs. It was thought that some of the features revealed were of general significance, as has been suggested, for example, in the section on the mineral oils; that the differences found between the lubricants

would appear in other applications; and that there would be direct applicability to some of the mechanisms in which plain sliding occurs with high pressures at the points of contact. It was not expected that the results would be directly applicable to gearing, because the motion in this apparatus is different from that between gear teeth; at the same time it was considered that the results should approach those for gear teeth at loads causing nearly instantaneous seizure, under otherwise similar conditions, as the influence of the superimposed rolling motion for the gear teeth would then become very small. It was in this respect that an oil with a flatter seizing-time-load curve was regarded as having a relative advantage; only this general inference was drawn, however, as the loads causing breakdown in specific very short times were not precisely determinable.

As far as extreme-pressure lubricants were concerned, it seemed that the speed of sliding might be too low, as several papers had brought out the importance of speed in its effect on temperature at the contacts, the good qualities of these special lubricants appearing only at relatively high temperatures. Against this the rating of the various classes of lubricants was undoubtedly in the right order, the hypoid gear lubricants showing seizure characteristics appropriately superior to the others; further, the appearance of the impressions showed that high temperatures had actually been reached at the contacts. As regards the first point, however, it was possible that the results were qualitatively in order, but not quantitatively represented, and as regards the second, that the high temperatures were the result of time and the absence of rolling motion, whereas high temperatures were required to be developed in a fraction of a second to represent hypoid gear teeth. Van Dijck and Blok [4] have suggested, however, that the high intensity of pressure at the contacts may compensate for the low speed, and give for the highest loads a rate of heat generation comparable with that of the S.A.E. machine, which gives the nearest experimental approach to the conditions of the hypoid gear. It seems, therefore, that the results may be of more direct utility than was at first apparent.

Further, and more generally, Blok has recently claimed that rating lubricants according to the breakdown load giving seizure even in as long a time as $2\frac{1}{2}$ seconds represents the behaviour in gearing, including the hypoid type. The evidence for this is not yet available, but it follows from the arguments above that it is not unreasonable, and a list of the "$2\frac{1}{2}$-second" breakdown loads for the lubricants tested in this investigation is given in Table II. The $2\frac{1}{2}$-second interval is not as short as would have been thought desirable, but it does take account of the slope of the seizing-time-load curve, and it is possible to read off the load at this interval more accurately than at shorter intervals. Nevertheless the accuracy is not great, owing to the scatter of the results, particularly in the case of the extreme-pressure lubricants; it is important to keep this in mind in comparing oils of similar breakdown loads.

Generally the engine oils, gear oils, and early extreme-pressure lubricants maintain their previous relative positions. Some of the gear oils gain considerably from flat seizing-time-load curves, but not generally so much as the early extreme-pressure lubricants. The most striking feature of the table is, however, the position of the recent extreme-pressure lubricants, which occupy a low position again, due to the relatively low load at

which friction rise is first found. As remarked before, this is not quite a fair comparison, as the rise of friction is not nearly so high as when the full seizure occurs in the other cases. It follows from this that the 2½-second breakdown load is unsatisfactory for the recent extreme-pressure lubricants

TABLE II.

The "2½-Second" Breakdown Load.

Lubricants.	2½-Sec. Breakdown Load, kg.	Ordinary Breakdown Load, kg.
B.P. Paraffin	50	40
Mineral Engine Oils:		
Dried Oil (winter)	60	50
Oil H2 (winter)	60	40
Oil J (summer)	60	40
Oil B (summer, solvent refined)	65	55
Oil A (summer, conventionally refined)	75	60
Oil H1 (winter)	80	65
Gear Oils:		
Base Oil X (mineral)	75	60–65
Oil X (ZnO addition)	85	75
Base Oil Y (mineral)	85	65
Oil Y (ZnO addition)	80	65
Oil G (mineral)	80	55
Oil JXB (partly-refined, mineral)	110	75
Castor Oil	110	75
Early E.P. Lubricants:		
E.P. Oil B	135	75
E.P. Oil A	145	110
E.P. Oil C	160	90
Recent E.P. Lubricants:		
E.P. Oil G (hypoid)	95	60 *
E.P. Oil E (hypoid)	110	80 *
E.P. Oil F (general purpose)	150	95 *

* Based on seizing time curves.

in that it introduces the time to "seizure," which is not a comparable feature and leaves out of account other valuable qualities of these oils.

ACKNOWLEDGMENT.

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[1] "General Discussion on Lubrication and Lubricants," 1937, **2**, 34. Inst. Mech. Engrs.
[2] *Ibid.*, p. 274.
[3] *Engineering*, 1933, **136**, 46.
[4] *Proc. 2nd World Petroleum Congress, Paris*, 1937, **3**, 445.

PRACTICAL METHODS OF TESTING LUBRICANTS.*

By J. H. Evans.†

The efficient lubrication of anti-friction bearings may be effected by any of the following types of lubricant :—

1. Lime-soap grease.
2. Soda-soap grease.
3. Mixed-base grease.
4. Aluminium stearate.
5. Mineral oils of varying degrees of refinement from light to heavy cylinder stock.
6. Lead soap and extreme pressure-type oils and greases.

Of these, lime- and soda-soap greases are the most widely used, and between them probably account for over 95 per cent. of the grease-lubricated applications.

Much has been written of the advantages and disadvantages of these two greases, and considerable experimentation has taken place to improve the characteristics of each. This has resulted in greatly improved products.

In the early days most greases were prone to exude mineral oil on standing and under service conditions, whilst they also thinned down excessively or completely separated into their component parts when slightly heated.

In addition, enclosures were often inefficient, and the separated oil ran out, with disastrous effects in automobile-wheel applications.

It was mainly on account of the instability of lime-soap greases that soda-soap greases became so widely used. Another factor in favour of soda-soap greases was their long, stringy, fibrous texture, as this formed an additional seal and prevented the separated oil from leaving the enclosures.

Soda-base greases, however, are easily washed out of the enclosures by excess of water, leaving the highly ground bearing-elements unprotected and free to corrode. In addition, many of these fibrous greases channelled badly in cold weather; consequently the bearings, operating without adequate lubrication, soon overheated, and in many cases seizure of the component parts resulted.

These conditions did not exist where a good-quality lime-soap grease had been used, and the co-operation of the grease-makers was sought to improve, and eventually standardize on greases of this type.

In accordance with this procedure, it soon became apparent that specifications and standardized testing methods were both desirable and necessary if the maximum benefits were to be obtained.

Lime-soap greases showed considerable variation in consistency, and it was felt that this characteristic should be the first to receive attention. Unfortunately there was no universal standard method for checking this property, and after careful consideration it was decided to adopt the same

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† British Timken, Ltd.

method as that employed by our associated American company—namely, the Karns Maag consistometer.

A photograph of this apparatus is shown in Fig. 1. The consistometer is made up of an alloy base 6 ins. × 9 ins., with a centring device for the grease-cup, and an upright $16\frac{1}{2}$ ins. high, to which is attached a projection for a release device. A metal ball is held in place by this arrangement 12 ins. above the surface of the grease, and can be released by pressing a trigger.

The cup is filled with grease levelled and heated to 75° F. for 1 hour, centred, and the ball is then allowed to fall freely into it. The depth of penetration is measured in millimetres direct from the rule attached to the

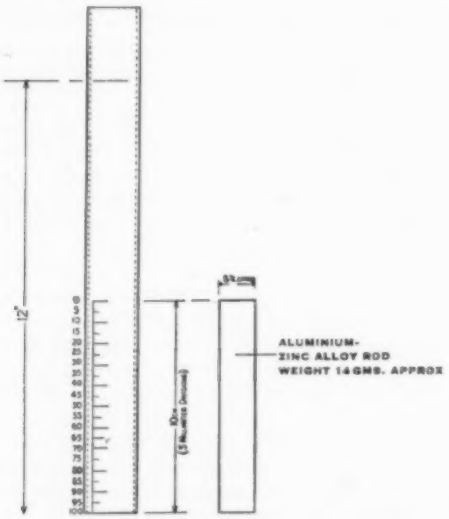

FIG. 2.

saddle-gauge, as shown in the photograph. The other parts of the apparatus are used for testing the consistency of hard block greases and the like.

A much simpler device giving concordant results with the Karns Maag was later suggested by E. A. Evans of Messrs. Wakefields. An illustration of this is shown in Fig. 2. It consists of a piece of ordinary burette tubing with a mark scribed 12 in. from the bottom. A millimetre paper scale 100 mm. long is attached to the bottom of the tube as shown.

The plunger is an aluminium alloy rod 100 mm. long, and it is allowed to fall freely down the tube from the scribed mark into the levelled sample of grease.

The depth of penetration is read off direct in millimetres from the top edge of the plunger to the millimetre scale.

The results are identical with those obtained on the Karns Maag.

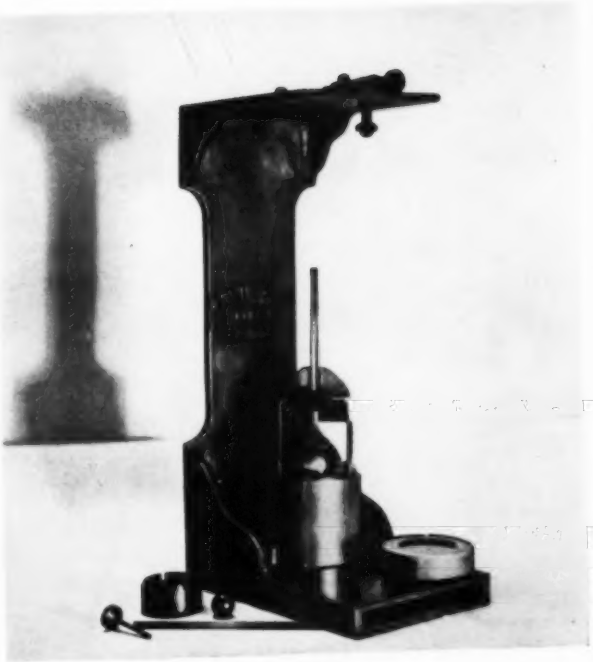

FIG. 1.

KARNS MAAG CONSISTOMETER.

[*To face p.* 730.

Consistency tests are taken on the grease as received and also after working (60 double strokes) in the standard grease-worker.

The I.P.T. and A.S.T.M. Grease Penetrometer is also used, and readings between 225 and 270 agree fairly closely with the specified 15–23 Karns Maag.

The effect of heat on the consistency on lime, soda, and various other types of grease is given in Table 1.

TABLE 1.

Consistency.

(Plunger readings in mm. = Karns Maag at ° F.).

	Grease.											Mixed Soda and Lime.	Lime Latex.	Aluminium Stearate.
	Lime Soap.					Soda Soap.								
° F	A.	B.	C.	D.	E.	F.	G.	Ha.	Hb.	J.				
70°	15	27	15	20	17	11	14	15	30	16		21	21	42·5
80°	19	30	16	23	17	12	17	20	35	20		25	25	47
90°	22	34	18	25	21	15	21	23	37	22		29	27	65
100°	26	36	22	27	22	17	24	27	49	25		31	30	—
110°	30	41	25	31	25	22	29	35	55	26		34	35	—
120°	32	45	26	35	27	26	35	41	67	29		37	37	—
130°	35	49	29	40	30	29	40	55	—	30		40	42	—
140°	38	50	35	42	37	32	44	70	—	31		30	45	—
150°	39	55	42	46	42	41	48	—	—	31		30	50	—
160°	42	56	62	50	45	50	60	—	—	32		30	53	—
170°	45	60	—	50	47	54	—	—	—	37		27	60	—
180°	52	—	—	50	50	57	—	—	—	42		22	—	—
190°	65	—	—	50	52	62	—	—	—	—		17	—	—
200°	—	—	—	62	57	—	—	—	—	—		15	—	—

Remarks.

Ha. Reading taken immediately on falling.
Hb. Reading taken after 1 min. interval.
J. Very fibrous grease.
Mixed soda and lime. Grease stiffens at 140° F.
Lime latex. Stringy texture.
Aluminium stearate. Semi-fluid.

Standardization of the method for determining moisture next received attention. Originally it was contended that at least 2 per cent. water was necessary to ensure complete hydration of the lime, but, as assumption yielded to experiment, it was soon found that by using correctly hydrated lime it was possible to manufacture grease in bulk with a water content of less than 1 per cent. This figure was therefore fixed as a maximum. The method fixed for determining the moisture was the Dean and Stark Distillation Method using gasoline as solvent.

Ash content was fixed at 2 per cent. maximum calculated as oxide.

The question of separation of mineral oil on standing and heating had still to be considered, as although great improvement in the quality of the grease had resulted from controlling the properties already mentioned, separation of oil from the soaps sometimes occurred.

Eventually the following method for estimating the separated oil was evolved :—

25 gms. of grease are placed in the standard Pensky–Martin flash-point cup and heated at the rate of 10° F. per minute to 250° F. The grease is maintained at this temperature for ½ hour. During heating and maintaining the grease is stirred at the rate of 2 revolutions per second for alternate minutes. It is then poured into a silica tube approximately 3 ins. long by 1 in. inside diameter, one end of which is sealed with a cork. After ½ hour atmospheric cooling the cork is removed and the grease, supported by two pieces of flattened wire $\frac{1}{16}$ in. wide, wound vertically round the tube, is suspended over a conical measure graduated in c.c.s. No separation of mineral oil is allowed after 48 hours cooling.

Melting-point determinations are made by the Ubbelohde method, in which the drop point is recorded. A minimum temperature of 210° F. was fixed.

Acidity or Alkalinity.—It has been established that free fatty acid—calculated as oleic—up to 0·5 per cent. has no injurious effect on anti-friction bearings. Most lime-soap greases are, however, slightly alkaline, and alkalinity up to 0·14 per cent. CaO is approved.

Corrosion tests in which copper and steel plates are submerged in the grease for 48 hours at atmospheric temperature should show no pitting or corroding.

Useful information can often be obtained by studying the behaviour of the grease when submitted to a heat-stability test. A recommended test is similar to the separation test already described, except that half of the grease is poured on to a cold watch-glass direct from 250° F. The other half is heated up to the fire-point of the base oil, and then also poured on to a cold watch-glass. If the greases show any oil separation, appreciable hardening or softening from 250° F., they are rejected, whilst it is found that most greases submitted to the fire-point test show no oil separation, but appreciable hardening. Little work is necessary to bring these back to perfectly good lubricants.

Lime-greases are also checked for emulsion-forming properties by shaking up with hot and cold water. Greases showing any emulsification are rejected.

The mineral oil is extracted and its physical characteristics are determined. The most satisfactory type of base is a well-refined mineral oil having a minimum viscosity of 420 seconds Redwood at 100° F. Open-flash, min. 340° F. Fire point, min. 380. Cold pour, max. 40° F.

With the advent of these new non-separating lime-base greases, it was found that for practically all automotive, locomotive, and many industrial applications, only one grade of grease was required. This is a smooth, well-milled product composed of high-grade soap and a refined filtered mineral oil of the viscosity mentioned above. The grease must be free from fillers of all kinds. Other physical properties as mentioned under their respective headings.

Soda-base Greases.

Greases compounded from mineral oil and soda soaps are recommended for applications where the operating temperatures are high and enclosures mperfect.

When high temperatures are encountered, it is advisable to ensure that they are not an effect of over-tightening of the bearings, incorrect clearances in associated component parts, or too much lubricant in the housing.

Fibrous, string-texture soda-soap greases are prone to track in cold weather, leaving the bearings dry and liable to burn up. They also retard the action of the revolving elements in the bearings, thus generating a greater amount of heat, as well as absorbing more motive power.

The type of soda-soap grease found most suitable has the following characteristics :—

Consistency	15–25 Karns Maag.
Moisture	max. 0·3%
Melting Point	min. 300° F.
Soda soap	15–18%
Base oil	
Viscosity at 100° F.	approx. 420 secs. Redwood.

Other properties, with the exception of emulsification, are similar to lime-soap greases. The grease must be a smooth, cold-milled product of short-fibre texture and free from all fillers.

Mixed-Base Greases.

Frequently 3–5 per cent. of lime soap is added to soda-soap greases to improve the appearance of the grease and give it a smooth, buttery, non-grainy texture similar to that of lime-base grease.

These products are stable, and have melting points intermediate between lime- and soda-soap greases. They are best compounded from Pennsylvania pale oil of approximately 300 secs. Redwood viscosity at 100° F. Melting points are generally in the region of 150° C.

Sometimes small percentages of aluminium stearate are added to lime-soap greases to improve heat stability.

Aluminium Stearate Greases.

These greases are generally used for aircraft rocker-arm bearings and variable-pitch propellers. Samples recently examined had the following physical properties :—

Moisture	0·1–0·3
Ash	0·8–1·0
Aluminium soap	15–18%
Melting point	212° F.
Separation	Nil
Emulsification	Nil
Alkalinity	Neutral
Open flash	515° F.
Fire	575° F.
Consistency	35 mm. Karns Maag—others too thin.
Mineral-oil base	Viscosity at 210° F. 150 Redwood secs.

In estimating the aluminium it is generally sufficiently accurate to dissolve the ash in boiling water, filter, burn, and weigh as Al_2O_3, ignoring any trace of iron which may be present.

The advantages claimed for aluminium-stearate greases over other types may not be justified, although they are generally accepted. Among them are the following: Melting point intermediate between lime- and soda-soap greases; water repellant—similar to lime-soap grease: become more adhesive and cohesive on heating to near the melting point, whereas lime- and soda-soap greases tend to thin down considerably on heating: heat stable—they can be heated above the melting point, and return to their original consistency on cooling—in this respect they resemble modern lime-soap greases.

Many of these properties can be checked, but it is also advisable to test the corrosive effect of aluminium-stearate greases on copper and steel test-pieces. This has been found necessary as some aluminium stearates contain appreciable quantities of stearic acid. A method used to accelerate the corrosive action of these or any lubricant is to submerge the test-plates in the lubricant and heat to a temperature of 210° F. for several hours. This method often shows corrosion when it is not obvious on samples tested at ordinary atmospheric temperature.

There appears to be some difficulty in controlling the consistency of aluminium-stearate greases, and as this is partly a function of the speed of cooling during manufacture, careful control in production is necessary.

There is sometimes a tendency for these greases to thin down in storage, but on heating to their melting point they return to their original consistency.

Fillers.

The use of fillers such as talc, graphite, waxes, rosin, clay, or mica, is not recommended in any greases intended for use with anti-friction bearings, as they not only lap the components in, but continue wearing them away, causing frequent replacements.

The tests on the consistency of the various greases at increasing temperatures (Table 1) are most illuminating, as so much has been written on the advantages of soda-soap greases when running temperatures are high.

The soda-soap greases examined were grades universally recommended for the lubrication of anti-friction bearings, and the experiments show them to thin down more quickly on heating than lime-soap greases. The general softening range appears to lie between 140° and 160° F. and even though the melting points—as determined on new grease by the Ubbelohde method—are so much higher than the lime-soap greases, they thin down between these temperatures to such an extent that only very efficient enclosures could retain them.

The lime-soap greases soften gradually, and are more viscous at the higher temperatures.

As a point of interest the melting points of these greases were :—

Grease.	Drop point Ubbelohde, °C.
Lime-soap A.	98
„ B.	107
„ C.	99
„ D.	109
„ E.	107
Soda-soap F.	142
„ H.	172
„ G.	149
„ J.	155
Mixed Lime-soda	166
Lime latex	104
Aluminium stearate	100

Running Tests.

In these tests a bearing was run under 90·5 per cent. overloading conditions at 550 r.p.m., using each of the greases mentioned above as lubricants. The bearing and housing were filled with grease, and a top plate, carrying a thermometer, fixed in position to make an efficient seal. The thermometer contacted directly with the top face of the inner component of the bearing, and the temperature rise was read off every minute for the first twenty minutes or so, and then at frequent intervals until the rise became steady. The results are plotted in Figs. 3A and 3B as temperature rise above starting temperature against time in minutes.

The results confirm the consistency tests—*i.e.*, in practically every case the grease thins down between the rolling elements at a temperature of 140–180° F., irrespective of the type of grease used.

Lime-soap greases softened gradually without tracking, and eventually flowed through the bearings in a similar manner to oil giving equivalent lubrication

The soda-base grease (J.) tracked badly, whilst greases H. and F. absorbed considerable energy in the early stages on account of their fibrous texture (compare 3A and 3B between 20 and 40 min. under load), then thinned down at 140–160° F., to behave generally like lime-soap greases. They churned and rotated, showing a similar centrifugal tendency to lime-soap greases, with no further evidence of tracking.

The soda base G. was a cold-milled product resembling lime-soap in appearance and texture. This had the highest softening point, 170–190° F., and did not melt, although it thinned down considerably, and pieces of normal grease could be seen floating about in the semi-fluid mass round the bearings.

The mixed-base grease softened between 150 and 170° F., and showed a tendency to track during the early stages. It did not churn, consequently the temperature was lower, but the grease in contact with the rolling elements thinned down to the consistency of cream, with a gradual transition to the stiffer grease in the sheltered parts of the housing.

The lime-latex commenced to soften and churn between 160° and 180° F., and the grease in contact with the bearing thinned down, but, on cooling, regained the stringy texture. The temperature rise with this grease was the highest of those examined.

The aluminium-stearate grease is not a recognized or recommended anti-friction bearing-grease, and has been included in all the tests solely as a matter of interest.

Before leaving the question of greases for ordinary applications, it is interesting to note that experiments are being made in America with barium-soap greases. These greases are water-repellant, have a melting

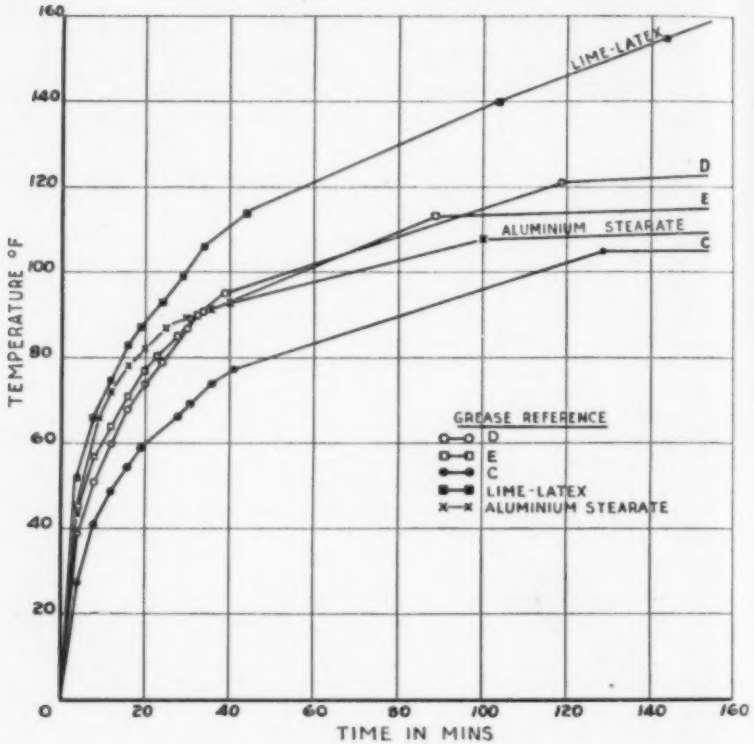

FIG. 3A.

LOAD TEST.

Lime Soap Greases.
Lime Latex.
Aluminium Stearate.

90·5% overload.
Speed 550 R.P.M.

point of over 300° F., and are similar in consistency and texture to lime-soap greases. It is expected that these greases, when fully developed, will prove an ideal lubricant for anti-friction bearings, as they possess the best properties without the respective disadvantages of soda- and lime-soap greases.

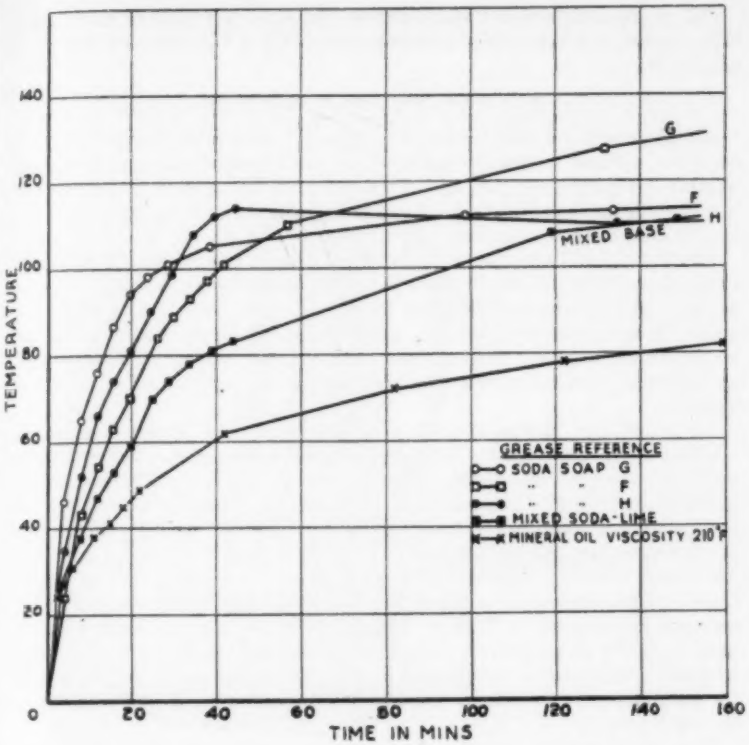

FIG. 3B.

LOAD TESTS.

Soda-Soap Greases.
Mixed Soda-Lime Greases.
Mineral Oil

90-5% overload.
Speed 550 R.P.M.

MINERAL OIL.

No special tests are necessary when checking mineral or compounded oils. Experience proves that the lubricants used, under normal loading conditions, are entirely satisfactory for the lubrication of anti-friction bearings. The viscosity range of oils found satisfactory in service varies between 60 and 170 secs. Redwood at 210° F., depending on the size, load, and speed of the application.

RAILWAY BEARINGS.

Oil is recommended for the lubrication of axle-box bearings, but in certain applications, where it has been found impracticable to make boxes oil-tight, standard lime-soap greases compounded from a base oil of 420 secs. Redwood at 100° F. have been found perfectly satisfactory.

Oil, giving satisfaction under different climatic conditions in many parts of the world, is a well-refined straight-mineral oil of 125–150 secs. Redwood at 210° F.

Extreme-Pressure Lubricants.

No discussion on the testing of extreme-pressure lubricants could be complete without mention being made of the Timken Wear and Lubricant Testing Machine (see Fig. 4). This machine was specially designed to measure the load-carrying capacity of lubricants, both oils and greases, when loaded near to their boundary film strength.

The Lubricant Tester illustrated in Figs. 4 and 5 was originally developed in the laboratories of the Timken Roller Bearing Company during a series of tests on the effect of different lubricants on hypoid and spiral bevel-gears in automotive axles. It provides accurate information on the load-carrying capacity of lubricants, on the measurement of friction, and, in a simple accurate manner, on the wear characteristics of any kind of material

The container, mounted on top of the base, holds about $\frac{1}{2}$ gallon of lubricant. Directly under it is an electric plate-heater which will raise and hold the contents of the container at any desired temperature from ambient to 250° F. In operation, oil from the container flows over the test-piece to a sump in the base. It is then pumped back by means of a small pump located in the base, and driven from the testing mandrel. The latter extends longitudinally through the base, and may be either direct- or belt-driven by a 2-h.p. synchronous-speed electric motor. The mandrel is mounted in Timken tapered roller bearings so arranged as to hold it rigidly in alignment, and is tapered at the end opposite the pulley to receive the tapered test-piece or cup. The latter is held firmly in place by a circular nut (left-hand thread), which screws on to the mandrel as shown in Fig. 4.

The lever system consists of two levers, one above the other. The upper is known as the load lever, and the lower as the friction lever. The upper, which carries the test-block holder, is pivoted on a knife-edge mounted in the lower lever. The latter is also pivoted on a universal knife-edge and provided with a stop at the unloaded end. The friction lever is provided with a vernier scale and a sliding weight for obtaining accurate measurements, and both levers are supplied with weight-pans. By virtue of this arrangement the test-block is always in the same relative position to the revolving cup, and the unit loading over the length of the two test-pieces is always constant. The test-block is inserted in a notch in the holder and held firmly in place by a wedge. For testing lubricants the test-pieces consist of a cup of a size that fits accurately on the mandrel, and the block, which is a $\frac{1}{2}$ in. square by $\frac{3}{4}$ in. long. Both test-pieces are made of steel, hardened to 60° C. Rockwell and ground. Four tests can be run with one test-block, but each new face tested requires a new cup on the mandrel. The cups can be reground. Newly ground faces on both pieces are necessary to ensure uniform results, and in no instance must the finish of the test components be altered.

The operation of the lubricant tester is substantially as follows :—

Assuming both test-pieces in place, the lubricant heated to the desired

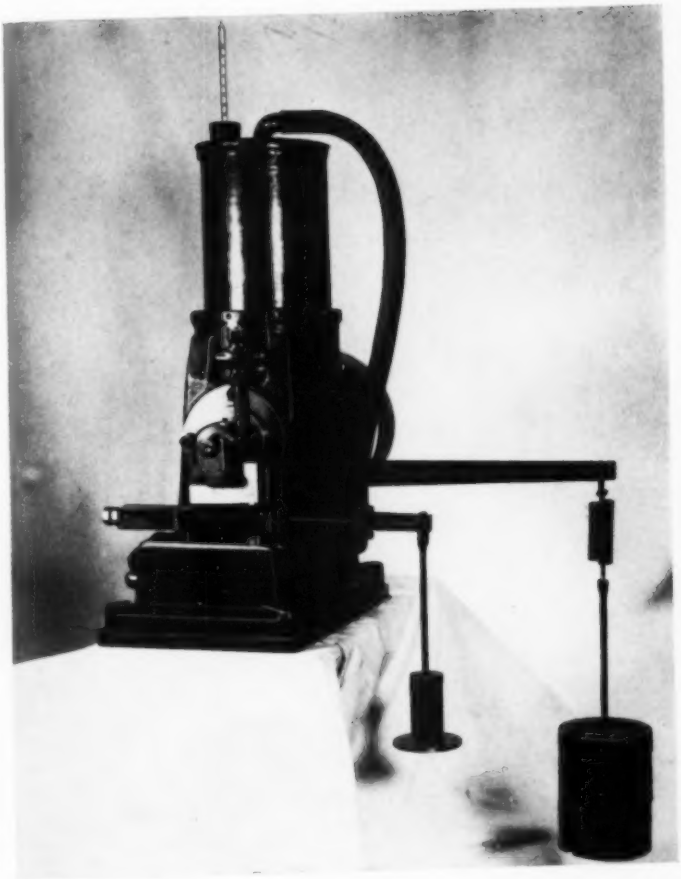

FIG. 4.

TIMKEN WEAR AND LUBRICANT TESTING MACHINE.

[*To face p.* 738

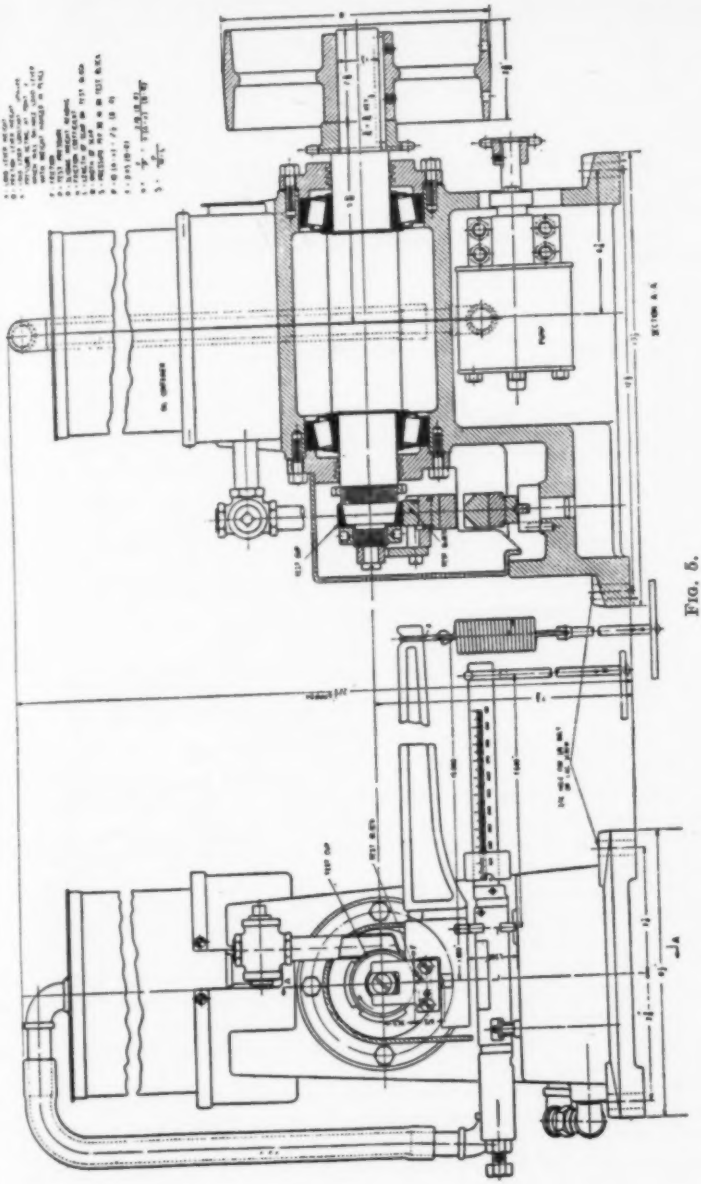

FIG. 6.

temperature, and allowed to flow over the test-block, the driving motor is brought up to the required speed. The loading lever is then loaded by means of weights until the desired unit pressure at the predetermined rubbing speed is obtained. It is important that the total testing load should be applied at once, rather than by gradually adding weights to the load lever, since it is the first few seconds of operation which determine the possibility of sustaining loads when near the scoring point.

A load test is usually run for a period of ten minutes. The surface of the block after test is examined, and if it is badly abrased or scored, the applied load has been too high for the lubricant under test.

The usual speed for testing lubricants is 400 f.p.m. (800 r.p.m. of the spindle).

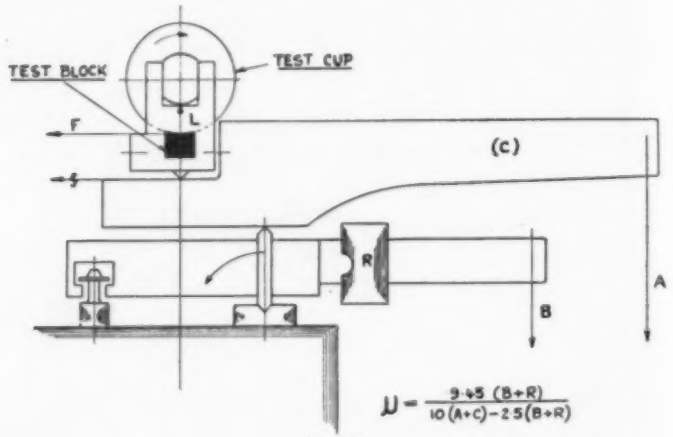

FIG. 6.

Greases can be tested by using the oil splash-guard surrounding the test-pieces and filling it with grease before commencing the test. The guard is then kept filled by continually adding grease by means of a grease-gun. To make grease tests comparative, care has to be taken to feed the grease at a constant rate.

Friction depends on loads, temperatures, rubbing speeds, and lubricant. Changing any one of these may affect the friction. To find the friction, weights are added to the (friction lever) weight-pan, or, if the friction is very small, the sliding weight is moved along the lever until the lever just leaves the stop-pin. Knowing the weight on the load lever and the friction lever, the normal load and the friction at the test-surfaces can be determined. After having found these forces, the coefficient of friction can be obtained.

To ensure that the test-pieces contact over the full width of surface, an adjustable universal knife-edge carries the lever system at the base of the machine.

The normal load on the test-pieces produced by the weight A (Fig. 6) on the end of the load lever creates a friction force at right angles to the

normal load depending on the rubbing speed, pressure, and lubricant used. This load, in turn, creates a force on the knife-edge resting on the top of the load lever, which is transferred to the knife-edge at the top of the friction lever. This tends to rotate the friction lever in a counter-clockwise direction, which is resisted by a stop-pin fixed to the base of the machine. To measure the friction, weights B are added to the bottom lever until it is just balanced (until the lever just leaves the stop-pin). The coefficient of friction can then be calculated from the formula:

$$M = \frac{9{\cdot}45 \times (B + R)}{10 \times (A + C) - 2{\cdot}5(B + R)}$$

where A = load on end of top lever,
B = load on end of friction lever,
C = load lever constant, and
R = friction lever sliding weight.

TABLE 2.

Load on Beam Arm in lbs.	12	18	25	33	43	51	59	68	77	86	96	105
Scar Width	Pressure in lbs. per sq. in.											
·021 in.	11,500	17,250	23,750	31,500	41,000	48,500	56,250	64,750	73,500	82,000	91,500	100,000
0·6 mm.												
·023 in.	10,500	15,750	21,750	28,750	37,500	44,500	51,250	59,250	67,000	74,750	83,500	91,500
·025 in.	9,750	14,500	20,000	26,500	34,500	40,750	47,250	54,500	61,750	68,750	76,750	84,000
0·7 mm.												
·027 in.	9,000	13,250	18,500	24,250	32,000	37,750	43,750	50,500	57,000	63,750	71,250	77,750
·029 in.	8,250	12,500	17,250	22,750	29,750	35,000	40,750	46,750	53,000	59,250	66,250	72,500
0·8 mm.												
·031 in.	7,750	11,500	16,250	21,250	27,750	32,750	38,000	43,750	49,750	55,500	62,000	67,750
·033 in.	7,250	11,000	15,250	20,000	26,000	31,000	35,750	41,250	46,750	52,000	58,250	63,750
0·9 mm.												
·035 in.	6,750	10,250	14,250	18,750	24,500	29,250	33,750	39,000	44,000	49,250	55,000	60,000
·037 in.	6,500	9,750	13,500	17,750	23,250	27,500	32,000	36,750	41,750	46,500	52,000	56,750
1·0 mm.												
·039 in.	6,150	9,250	12,750	17,000	22,000	26,000	30,250	35,000	39,500	44,250	49,250	54,000
·041 in.	5,850	8,750	12,250	16,000	21,000	24,750	28,750	33,250	37,500	42,000	46,750	51,250
1·1 mm.												
·043 in.	5,500	8,250	11,500	15,250	20,000	23,750	27,500	31,750	35,750	40,000	44,750	48,750
·045 in.	5,350	8,000	11,250	14,750	19,250	22,750	26,250	30,250	34,250	38,250	42,750	46,750
1·2 mm.												
·047 in.	5,250	7,750	10,500	14,000	18,250	21,750	25,000	29,000	32,750	36,500	40,750	44,750
·049 in.	5,000	7,250	10,250	13,500	17,500	20,750	24,000	24,000	27,750	31,500	35,250	43,000
1·3 mm.												
·051 in.	4,750	7,000	9,750	13,000	17,000	20,000	23,000	26,750	30,250	33,750	37,750	41,250
·053 in.	4,500	6,750	9,500	12,500	16,250	19,250	22,250	25,750	29,000	32,500	36,250	39,750
1·4 mm.												
·055 in.	4,350	6,500	9,000	12,000	15,500	18,500	21,500	24,750	28,000	31,250	35,000	38,250
·057 in.	4,250	6,350	8,750	11,500	15,000	17,750	20,250	24,250	27,000	30,250	33,750	37,000
1·5 mm.												
·059 in.	4,000	6,000	8,500	11,250	14,500	17,250	20,000	23,000	26,000	29,250	32,500	35,600
·061 in.	3,950	5,900	8,200	10,750	14,000	16,750	19,500	22,250	25,250	28,250	31,500	34,500
1·6 mm.												
·063 in.	3,800	5,750	8,000	10,500	13,500	16,250	18,750	21,500	24,500	27,250	30,500	33,250
·065 in.	3,700	5,500	7,700	10,250	13,250	15,750	18,250	21,000	23,750	26,500	29,500	32,250
1·7 mm.												
·067 in.	3,600	5,500	7,500	10,000	12,750	15,250	17,500	20,250	23,000	25,750	28,750	31,250
·069 in.	3,500	5,350	7,250	9,500	12,500	14,750	17,000	19,750	22,250	25,000	27,750	30,500
1·8 mm.												
·071 in.	3,400	5,000	7,000	9,250	12,000	14,250	16,500	19,000	21,750	24,250	27,000	29,500
·073 in.	3,300	4,900	6,850	9,000	11,750	14,000	16,250	18,500	21,000	23,500	26,250	28,750
1·9 mm.												
·075 in.	3,200	4,750	6,750	8,750	11,500	13,500	15,750	18,000	20,500	23,000	25,750	28,000
·077 in.	3,100	4,675	6,500	8,550	11,250	13,250	15,200	17,650	20,000	23,350	25,000	27,250
2·0 mm.												
·079 in.	3,000	4,550	6,250	8,250	11,000	13,000	15,000	17,250	19,500	21,750	24,250	26,500

1 mm. = ·0394 inches.

When conducting wear tests, the weights of the cup and block are taken before and after the test run, to determine the amount of metal removed.

Formulæ are provided by which the results obtained on the machine can be readily converted into lb. per sq. in. and the coefficient of friction determined.

The chart drawn up in Table 2 shows the load in lb. per sq. in. from lever load and scar width.

Mineral Oils.

It has been demonstrated by Maag [1] that the film strength of a straight uncompounded mineral oil is directly related to the viscosity as is shown in Table 3.

Table 3.

Viscosity. Saybolt at 210° F.	Load on Lever Arm.	
	O.K. Load.	Score.
40	1	2
48	5	6
65	7	8
73	9	10
99	11	13
124	13	15
153	15	17
180	18	20

The effect of additions of various metallic soaps and esters on the film strength of a mineral oil of 125 secs. Redwood at 140° F. were investigated by E. A. Evans;[2] using the Almen Machine.

Experiments on the Timken Machine to check these results using the same viscosity mineral oil with similar additions gave the following results:—

Table 4.

	Almen M/c.	Timken.		
		O.K.	Score.	Approx. lb. per sq. in.
Film strength of mineral oil	—	6	7	4300
Metallic Soaps:				
5% lead oleate	3,000	7	8	4800
5% sodium oleate	4,000	6	7	4300
5% tin oleate	5,000	8	9	5600
5% aluminium oleate	8,000	8	10	5600
5% chromium oleate	13,000	8	9	5600
Esters:				
3% ethyl phthalate	9,000	9	10	6100
3% butyl phthalate	5,000	9	10	6100
3% methyl salicylate	10,000	8	9	5600
5% ethyl phthalate	9,000	10	12	6700
5% methyl salicylate	12,000	9	10	6100
5% butyl phthalate	—	11	13	7200

These results confirm those obtained by Evans, in so much as they prove the esters have more effect on the film strength than the metallic soaps. But even the esters do not increase the film strength sufficiently for them to be considered extreme-pressure lubricants.

It has been shown that film strength is a function of the viscosity of straight mineral oil; when an E.-P. base is added to the oil, however, viscosity is of secondary importance.

Extreme-Pressure Oils.

Extreme-pressure oils were primarily developed for the lubrication of hypoid gears, and although the use of such gears is not general in this country, there are indications that in the near future they will be more or less universally adopted.

Bearing this in mind, a few comments on the position of hypoid-gear lubrication as it is at present in America are given, in the hope that advantage may be taken of American experience.

For the past three years opinion has been divided between the advocates of an active sulphur hypoid oil and those preferring a mild-type E.-P. oil. Active sulphur hypoid oils are those which quickly tarnish a bright copper plate, whereas the mild-type E.-P. oils are more stable and less corrosive.

The mild types include sulphur-saponifiable combinations—*i.e.*, mineral oils containing approximately 20 per cent. of a sulphurized or chlorinated fatty oil base. Included in this group are also certain phosphorus compounds.

There has been, and still is, considerable diversity of opinion as to the respective merits of each type, but there are now definite indications that the active sulphur hypoid oils will be eventually superseded by the mild-type E.-P. oils. These oils are proving perfectly satisfactory in service, and as they are more stable and less corrosive than the hypoid oils, they have the advantage of being used in transmissions as well as rear axles.

At present about 9 gallons of mild E.-P. oil is sold to 1 gallon active sulphur type.

Table 5.

Lubricant.	Specimen.	O.K. Load, lb.	Wear, 6 hrs. with 33 lb. on Load Lever, gms.
Chlorinated oils . .	1	100 plus	0·0035
	2	95	0·0030
	3	100	0·0045
	4	95	0·0020
	5	59	0·0050
Sulphurized fatty oils .	1	43	0·0070
	2	43	0·0150
	3	33	0·0050
	4	33	0·0055
	5	43	0·0080
	6	43	0·0075

O. L. Maag [3] published in 1934 the results of some of his experiments on chlorinated and sulphurized fatty oil bases in mineral oil. These (Table 5) showed that as the percentage of chlorinated base is reduced, the load-

carrying capacity is also reduced, but the abrasiveness increases. The sulphurized oils are definitely more abrasive than the chlorinated, and also have a lower film strength.

Experiments have been conducted on a mineral oil of 65 secs. viscosity at 210° F. and varying percentages of hexachlorethane or certain proprietary E.-P. bases (A and B), of which there are now several on the market. The result of these experiments are given in Table 6.

TABLE 6.

Lubricant.	E.-P. Base, %	O.K. Load, lb.	Loss in weight at O.K. Load, gms.
Mineral oil . .	—	10	0·001
Hexachlorethane .	2½	60	0·006
	5	80	0·030
	7½	100 plus	0·009
Dope A. . . .	2½	40	0·003
	5	90	0·021
	7½	90	0·074
Dope B. . . .	7½	60	0·010
	10	60	0·015

GREASES.

Load tests on the greases used for checking consistency at elevated temperatures (see Table 1) gave the following O.K. values for the different types.

	Grease.	O.K. Load, lb.	Breakdown, lb.
Lime base . .	B.	11	12
	E.	12	14
	C.	12	14
	A.	15	17
	D.	12	14
Soda base . .	J.	7	8
	G.	6	7
	F.	12	14
	H.	14	16
Mixed base . .	—	7	8
Lime latex . .	—	13	15
Aluminium stearate .	—	13	17

While it is not claimed that the number of greases reported on above is exhaustive, it is representative—in the case of soda- and lime-soap products—of a large number of each type examined.

It has been repeatedly observed that the soda- and mixed-base grease show considerably more variation in film strength, and are generally appreciably lower, than lime-base grease. The two soda-soap greases H. and F., however, show that it is possible to compound this type so that they have equivalent load-carrying capacity to the lime-soap grease.

Extreme-Pressure Greases.

In the field of E.-P. grease lubrication successful results have been obtained with compounded lime and/or lead soaps plus mineral oil and sulphurized or chlorinated base products, used either singly or in combination, together with certain phosphorus compounds.

On account of the wide variety of chemical substances being used at the present time, it is inadvisable to mix different E.-P. greases in service.

When should an E.-P. grease be used?

In all lubricating problems the most adverse conditions should control the type of lubricant used, and E.-P. greases are recommended when abnormal loading conditions are expected in service. An example of this is furnished by the application of roller-bearings to rolling-mills. In some cases the separation force between the rolls is estimated to be in the region of 3,000,000 to 5,000,000 lb. and the use of E.-P. greases for the roll-neck bearings, and also gear drives and their bearings, is recommended.

The checking of these greases offers little difficulty; sulphur, chlorine, and lead soaps are estimated in addition to the usual chemical and physical tests. Satisfactory estimations of sulphur and chlorine have been found possible by using the Parrs Bomb if the usual precautions are taken.

Corrosion tests are more important than with ordinary greases, on account of the nature of the additives. A suitable test is to submerge the copper and steel test-plates in the grease and hold for 1200 hours at atmospheric temperature, or for a much shorter time at an elevated temperature, as previously mentioned.

Resistance to water. It is advisable to check this property very carefully, as some E.-P. greases take up large quantities of water—in fact, very few are truly water-repellant. It has been found that the characteristics of these greases in the presence of excess water vary considerably. Some thin down to such an extent that they would be quickly washed out of the bearings, whilst others absorb large quantities in forming emulsions of different degrees of stability.

To test this property, a quantity of grease is churned up with water, added a little at a time, and stirred until it is absorbed or the grease thins down. If an emulsion is formed which does not thin down, the addition of water is continued until free globules exist. The percentage water content is then checked by the Dean and Stark distillation method.

Some lead-lime-soap greases take up as much as 60 per cent. water and still retain their original consistency; others take up the same quantity before becoming saturated, but then exude water on standing until approximately 25 per cent. remains as a fairly stable emulsion.

Greases thinning down under this test are rejected.

The usual 1200-hours corrosion check is conducted on the emulsions, and those showing staining or corrosion are rejected.

In addition to these tests, those described under lime-soap greases are also made.

Load Test.

All E.-P. greases must carry a load of 43 lb. on the load-lever arm of the Timken machine in order to be approved. The ultimate breakdown load is also determined and recorded.

If the grease successfully passes this test, an abrasion test at 33 lb. for 2 hours is run. The test components are weighed before and after, to determine the loss in weight.

Finally a stability test is made on the grease used during the abrasion test. In this the ultimate load is checked. It is often found that the maximum load is much less than originally, and chemical analysis generally shows this to be caused by a reduction in the sulphur or chlorine content.

As appreciable heat is developed during the load tests, some of the unstable compounds break up, and cause serious staining or corrosion of the test parts. This condition is carefully noted, and also the load at which it commences.

Greases are not approved if they show staining at the specified load of 43 lb. on the lever arm.

Two lead-lime-soap sulphurized base greases recently examined, which formed emulsions, had the following characteristics :—

(Speed 800 r.p.m.; Time 10 minutes.)

Grease.	Load on Lever, lb.	Friction Load on Lever, lb.	Scar Width, mm.	Loss in Weight, grams.
A . . .	43	2·99	2·1	0·005
	45	4·22	Scoring badly.	—
2 hrs. test . .	33	1·4	2·45	0·011
Stability test .	43	Broke down.	—	—
	33	2·23	1·8	0·002
B . . .	43	2·80	2·2	0·012
	50	3·40	2·9	0·014
	70	4·30	4·2	0·037
2 hrs. test . .	33	1·45	3·0	0·010
Stability test .	43	3·00	2·6	0·015

Load Test on Emulsions.

Samples emulsified until saturated (both took 60 per cent. of water to saturate), and left to stand for 3 days before test.

Grease.	Load on Lever, lb.	Friction Load on Lever, lb.	Scar Width, mm.	Loss in Weight, grams.
A . . .	43	Broke down	—	—
	33	" "	—	—
	25	1·5	1·5	0·005
	28	Broke down	—	—
B* . . .	43	1·15	2·0	0·010
	55	2·60	2·2	0·013
	60	3·00	2·8	0·017
	70	3·25	3·2	0·025
	80	Broke down	—	—

* Slight staining at 55, 60, and 70 lb.

Moisture on Samples Tested.

Grease—A—exuded water on standing until 25 per cent. remained in solution. Grease—B—retained 60 per cent. in solution.

Corrosion after 1,200 hours—Greases A and B, nil.

It will be observed that the grease forming a stable emulsion (*B*) had the same load-carrying capacity as new grease, but the unstable emulsion (*A*) had a much lower film strength than originally.

When using greases of either type, saturation point is soon reached on rolling-mills where the rolls are flooded with coolant, particularly as it is difficult, if not impossible, to maintain perfect seals. The free water, existing as globules, is liable to cause corrosion of the highly ground bearing surfaces, and until a truly water-repellant E.-P. grease is available or, alternatively, designers of enclosures can produce a perfect seal which will prevent the ingress of water into the bearings, it is advisable to replenish the greases at comparatively frequent intervals.

As most modern mills are equipped with pressure-feed installation, this is not a difficult procedure.

Effect of Finish on Film Strength.

The test components used on the Wear and Lubricant Tester are deliberately made to a good-commercial-quality grinding finish, as this represents general industrial production.

It is fully appreciated that the load an oil film will carry is to a large extent dependent on the finish of the wearing surfaces. Different degrees of finish can be very easily obtained by the investigator as a means of checking the effect of similar finishes on components.

What is the effect of better finish to gears, crown wheels, pinions, cams, etc., on the film strength of a lubricant? The following experiments (Table 7) show to what a remarkable extent load-carrying capacity can be increased, friction reduced, and abrasion practically eliminated by merely improving the surface finish of the test components.

The cups used in these tests were polished on the spindle of the machine and the blocks hand polished.

Table 7.

Lubricant:—Motor Oil 66 secs. viscosity at 210° F.

Finish.	Temp. of Oil, ° F.	Load on Lever, lb.	Load on Friction Lever, lb.	Scar Width, mm.; Length, ins.	Temp. of Oil at End of 10 mins. ° F.	Load, lb. per sq. in.	Coefficient of Friction.
Rough grind .	100	5	0·44	1·0 mm. × $\frac{1}{4}$ in.	109	3,500	0·062
Standard grind .	102	10	0·89	1·05 mm. × $\frac{1}{4}$ in.	115	5,530	0·072
Standard I.F. Emery paper .	106	40	0·94	1·1 mm. × $\frac{7}{16}$ in.	121	21,600	0·0210
Standard I.F. plus 00 emery paper	102	50	1·08	1·2 mm. × $\frac{1}{4}$ in.	114	22,420	0·0197
Standard I.F. plus 00 and rouge .	101	55	1·07	0·9 mm. × $\frac{1}{4}$ in.	110	31,420	0·0185

These results are shown graphically in Figs. 7, 8, and 9. Fig. 7 shows coefficient of friction plotted against pounds on lever; Fig. 8 lb. per sq. in.

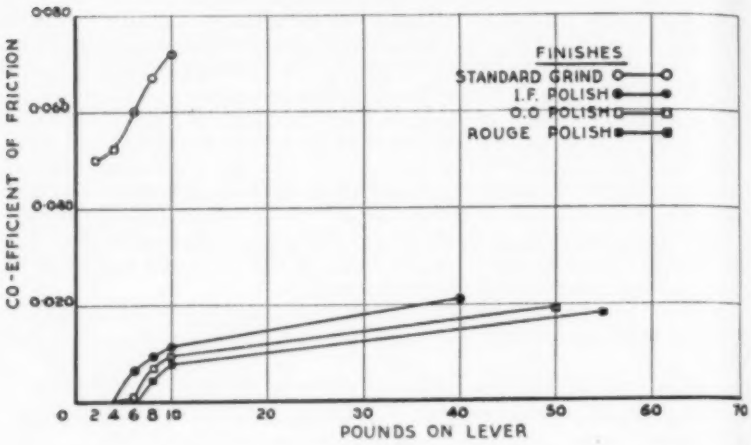

FIG. 7.

MOTOR OIL 66 SECS. VISCOSITY AT 210° F.

Effect of Polishing Cups.
Coefficient of Friction.

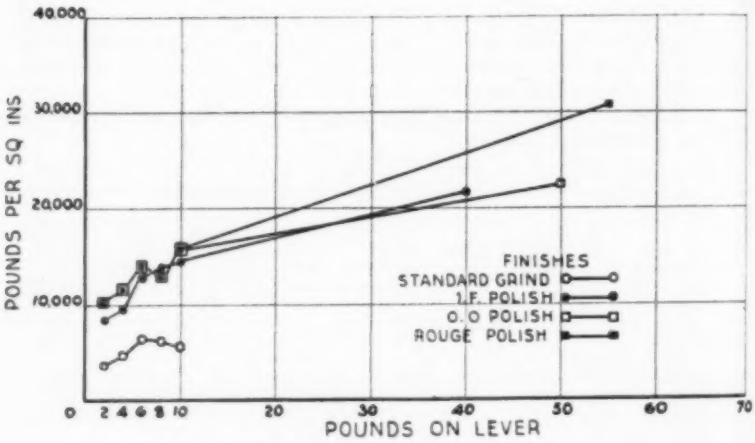

FIG. 8.

MOTOR OIL 66 SECS. VISCOSITY AT 210° F.

Effect of Polishing Cups.
Pressure lbs. per sq. ins. on actual scar area.

against lb. on lever; and Fig. 9 * increase in temperature of block against lb. on lever and increase in temperature of oil against lb. on lever.

The results of these experiments clearly show that the benefits derived from an improvement in surface finish would outweigh any extra cost entailed, by reducing the number of costly failures caused by abrasion or seizure. It would also, in a number of cases, negative the need for extreme pressure lubricants.

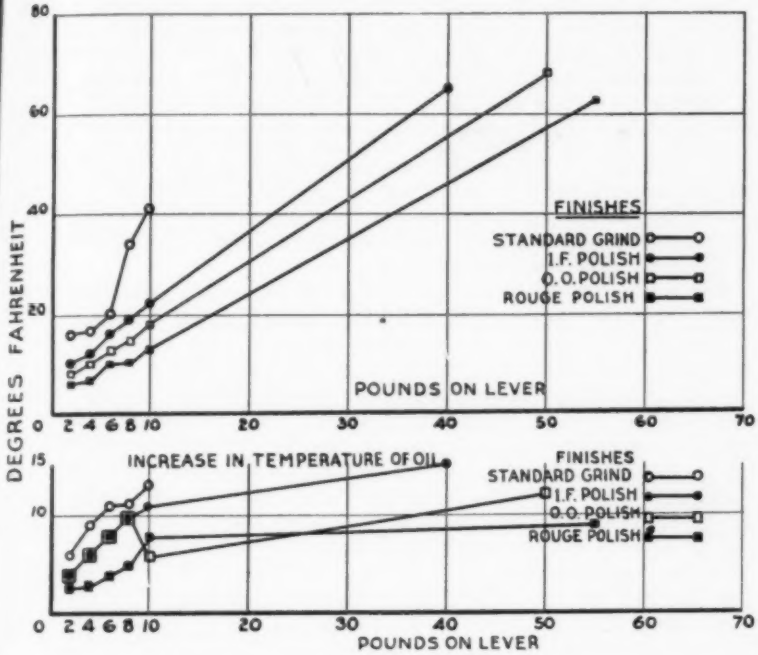

FIG. 9.

MOTOR OIL 66 SECS. VISCOSITY AT 210° F.

Effect of Polishing Cups.
Temperature rise of Block.

In numerous instances E.-P. lubricants are being used to procure this desired effect by their lapping action, and when the parts are properly "run in," the E.-P. doped oils are washed out and replaced by normal lubricants.

This does not mean that E.-P. lubricants are not necessary and here to stay, but it is intended to convey that they should only be used when experience proves their necessity, after a proper finish has been found insufficient to meet the loading requirements. Such cases may be hypoid

* The temperature of the block was taken with a thermometer at the end of the test run before dismantling the machine.

gears or special applications continually subjected to extremely heavy running and shock loads—*i.e.*, rolling-mill applications.

In concluding this extremely important part of the paper, the following comments, made by Dr. Vogel,[4] have been chosen out of the many references which have been made to surface finish during recent years.

Discussing results obtained on a special wear tester he had constructed, Dr. Vogel said :—

> "No wear of the unhardened test-pieces could be observed at a load of 300 kg. per sq. cm. after 12,000 revolutions, if the surface of the Böhler steel was polished like a mirror, which was in accordance with the observation that at an infinite number of revolutions—*i.e.*, when the surface was polished, the wear tended towards zero. The only lubricant used was air."

In conclusion, the effects of metallized surfaces on the film strength of an oil of 50 secs. Redwood at 210° F. have been investigated.

The test-pieces were standard cups, plated by electrolytic deposition, and the normal hard-steel test-blocks, finished I.F. emery paper.

The speed in all tests was 800 r.p.m.

The bright chrome was nickelled first, but the hard chrome deposited direct on to the steel.

TABLE 8.

Surface.	O.K. Load, lb.	Breakdown, lb.	Coefficient of Friction.
Standard steel cup and block	8	9	0·091
Tin	25	30	0·052
Copper	43	45	0·027
Cadmium	43	45	0·064
Hard chrome	30	33	0·080
Bright chrome	Peeled at 9 lb.	—	—
Nickel	Peeled at 7 lb.	—	—
Tests on bonderized and Parkerised cups :—			
Bonderized	50	55	0·075
Parkerized	60	65	0·071

The author wishes to place on record his thanks to the Directors of British Timken, Ltd., for permission to publish this paper; to Messrs. Wolseley Motors, Ltd., for the different plating finishes; to Messrs. Wakefield for the metallic soaps and esters; to Mr. O. L. Maag of the Timken Roller Bearing Company, Canton, for his continued advice on all problems relating to lubrication, and finally to Messrs. C. Thomas and A. Mould, members of the Laboratory Staff at British Timken, Ltd., for their valued assistance.

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[2] Evans, E. A., "Extreme Pressure Lubricants," I.Mech.E. General Discussions on Lubricants, Group III, 1937.
[3] Maag, O. L., "Industrial Lubrication and Lubricants." National Association of Lubricating Grease Manufacturers, Chicago, 1934.
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A TENTATIVE LABORATORY TEST FOR THE RING-STICKING PROPERTIES OF LUBRICANTS *

By J. C. McNicol,† C. G. Williams, M.Sc.,† and P. V. Lamarque, B.Sc.†

Synopsis.

A description is given of a simple laboratory test for assessing the oxidation and ring-gumming propensities of engine lubricants. The test, which consists principally in measuring the strength of a thin oxidised film of the lubricant, has been used for a preliminary study of the oxidation process over a range of temperatures and exposure times in the case of one lubricant, and at a fixed temperature in the case of a number of petrol- and diesel-engine lubricants of known service performance.

Although the information obtained so far is not extensive, it is shown that, in lubricants which are prone to cause ring-sticking in diesel engines, the strength of the oxidized film is much higher than in the case of lubricants giving comparative freedom from ring-sticking. In addition, it is shown that high film strength is associated with high viscosity index of the lubricant. In the limited number of petrol-engine lubricants examined, volatility appeared to be a better criterion than the strength of the oxidised film.

Introduction.

Piston-ring sticking is associated with the formation of oxidation products by the lubricant, and is influenced by mechanical and thermal conditions in the engine. The only completely satisfactory method of testing the stability and ring-gumming properties of engine lubricants is, therefore, on engines under appropriate operating conditions, but this method is experimentally difficult and expensive since it involves a prolonged study of the effects of operating conditions, detail mechanical design, and lubricating conditions. With these difficulties in mind, oxidation tests on engine lubricants were undertaken with a view to developing a simple laboratory test which, in the light of service experience, could be used for the rating of engine oils as regards their ring-gumming and oxidation propensities. The test adopted for this investigation was the simplest it was possible to devise—viz., a mechanical adhesion test subsequent to the oxidation of a small sample of oil, of the order of 0·25 gm., in an electric oven over the temperature range 180–240° C.

At the outset, attention should be directed to certain limitations of the test. In view of the comparatively high temperatures used, the test does not take into account the effect of prolonged low-temperature crank-case oxidation. Furthermore, some distinction should be drawn between lubricants for petrol engines and for compression-ignition engines. In the light of the known effects of combustion conditions and fuel characteristics on ring gumming and oxidation in compression-ignition engines, the simple test discussed must inevitably be inadequate, since it does not take into account the solvent or detergent properties of the lubricant. In so far as ring-sticking in compression-ignition engines is due to gum formation by the lubricant, the test may, however, be of some value.

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† Research Department, Institution of Automobile Engineers.

Although a service test is necessary before conclusive indication of the behaviour of a lubricant under particular conditions can be obtained, it should be possible, on the other hand, to use a simple test, such as that described in the present report, for the broad classification of lubricants for high-temperature conditions.

Description of Apparatus.

In the electric oven used for the tests (see Fig. 1) the heating elements were placed over two sides and on the floor, and separated from the free air space by perforated sheet metal. The oven had a total internal volume of 0·84 cu. ft., and a free air space of 0·58 cu. ft. The temperature was thermostatically controlled to within $\pm$ 2° C., and was read off a mercury thermometer projecting through the top of the oven into the free air space.

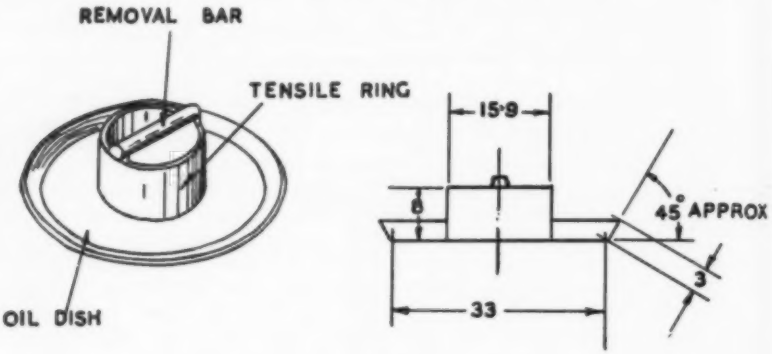

Fig. 2.

For simplicity, air circulation in the oven was uncontrolled, and was provided by two 1-in. holes in the floor and a 1-in. hole in each of the sides. A perforated copper shelf was also provided and, for the tests, was placed at about the middle of the oven.

An exploration of the temperature distribution in the oven revealed that, after soaking, the actual temperature of objects placed on the copper shelf was 11° C. above that shown on the mercury thermometer. This difference, which, with the exception of a narrow area in close proximity to the door, was uniform over the shelf, can probably be accounted for by conduction through the shelf. Over the whole shelf the maximum variation of temperature was 4° C.

To approximate to conditions on pistons and cylinders in actual engines, the tests were mostly carried out on comparatively thin films of oil. These conditions were obtained by introducing a small sample of the oil under test into a shallow steel dish which gave a ratio of exposed surface area to volume

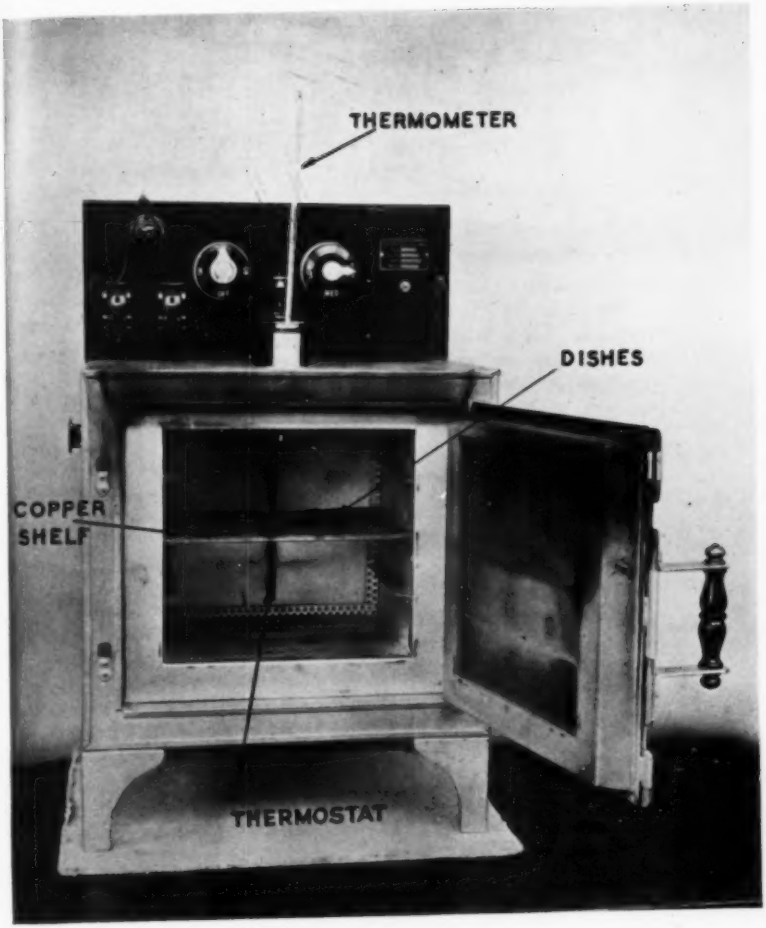

FIG. 1.

ELECTRIC OVEN USED IN TESTS.

[*To face p.* 752.

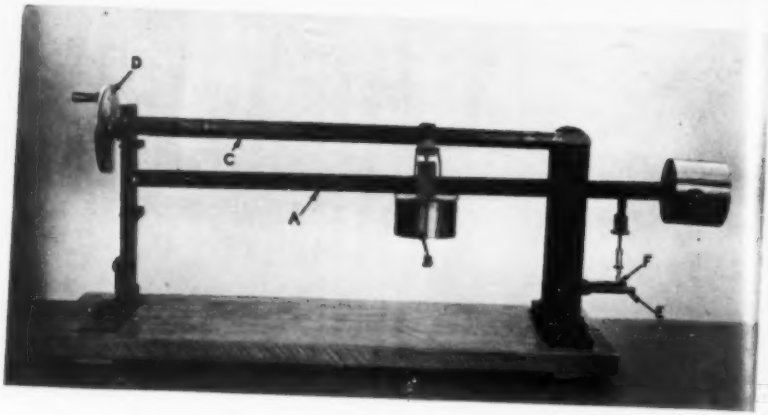

FIG. 3.
TENSILE MACHINE.

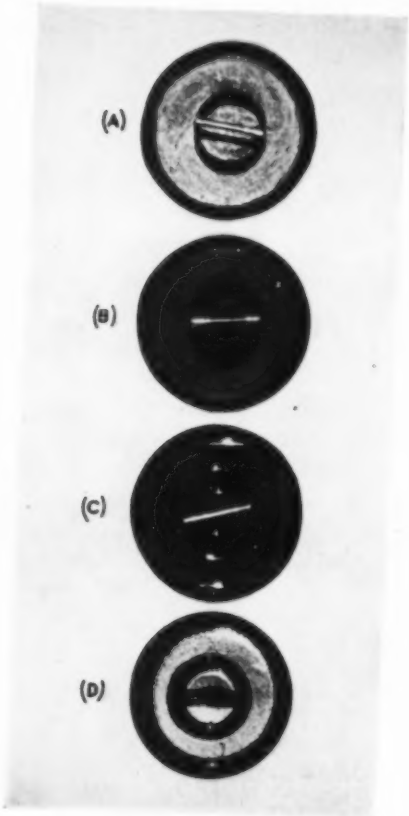

FIG. 4.
A. Dish and ring after cleaning.
B. Dish and ring after preliminary heating in oven.
C. Dish containing oil sample and ring ready for heating.
D. Appearance after oxidation.

of oil sample of about 30 sq. cm. per 1 c.c. of oil. A thin steel ring, bridged at one end by a bar, was also placed in the dish at the beginning of the test, the dimensions of the dish and ring being shown in Fig. 2. During the subsequent heating of the oil sample in the electric oven, the lighter fractions evaporated, leaving residues adhering to the ring and dish. Under engine conditions, the gum formed in the piston-ring grooves tends to harden on cooling of the engine, ring sticking becoming evident in subsequent operation. To simulate these conditions in the test, the dish and ring were allowed to cool before any attempt was made to disturb the residue formed. When the dish and ring were thoroughly cold, the force required to separate them was measured on the small tensile machine shown in Fig. 3. This machine consisted of the weighing lever *A*, mounted on a knife edge, and a jockey weight *B* which could be moved, either mechanically or by hand, by the control screw *C*. During the first few tests it was found that hand operation did not give a sufficiently uniform rate of load application, and the results were erratic. In all subsequent tests the screw was belt driven from an electric motor, through pulley *D*. The dish was placed under the fork *E*, and a hook *F*, connected to the weighing lever, engaged the bar bridging the open end of the ring.

As the investigation progressed, the effect of film thickness on the oxidation of the oil was also studied, together with the effect of prolonged heating. It should be noted that mild-steel dishes and rings were used throughout the tests, no study being made of the catalytic effect of other metals on the oxidation of the oil.

Test Procedure.

To ensure uniform surface conditions on the dishes and rings at the beginning of each test throughout the series, the following procedure was adopted. After pickling in dilute hydrochloric acid and rinsing in hot water, the dishes and rings were dried by hand and placed in the oven, which had already been stabilized at the temperature of the subsequent test, and heated for about half-an-hour until the surface had assumed a uniform colour. The dishes were then removed and allowed to cool, after which they were weighed with the rings in place. A $\frac{1}{4}$-gram sample of oil was transferred to the dish from a calibrated dropping pipette, the actual weight being determined by weighing the assembly before and after introducing the oil. The oven was always stabilized at the test temperature before placing the dishes inside, and these were allowed to heat up for 5 min. before the test was considered to have begun. In the early tests six oil samples were tested at a time, but later the number was increased to nine, the first six samples being removed at hourly intervals and the others after about 20–30 hr. The various stages of the test are indicated in Fig. 4, in which (*A*) shows the dish and ring after cleaning; (*B*) the same components after the preliminary heating in the oven; (*C*) the dish containing the oil sample and ring ready for heating; and (*D*) the appearance after oxidation.

After cooling, the combined dish and ring were, in each case, weighed to determine the evaporation loss, and the force required to separate them measured on the tensile machine, the load being applied at the rate of $\frac{1}{2}$ lb. per sec. A chemical examination was also made of the oxidation

products remaining in the dishes. In each case the residue was examined for solubility in petroleum ether and benzene. After treatment with these two solvents, there always remained a precipitate which represented the insoluble matter present in the residue. The procedure for the chemical examination was to transfer the sample obtained, after scraping each dish and its corresponding ring with a steel spatula, into a weighed boiling tube, which was then re-weighed to obtain the sample weight. Normally the sample consisted of about 70 per cent. of the residue present on the dish and ring. The contents of the boiling tube were then allowed to drain down to the bottom and the sides of the tube washed down with 10 c.c. of 60/80 aromatic free petroleum ether, refluxed for 30 min., and allowed to settle. The liquid was next decanted through a weighed Gooch filter, retaining as much of the solid matter as possible in the tube, and this solid matter washed with petroleum ether and again decanted. The total filtrate was then evaporated on a water-bath, dried at 120° C., and weighed. The residue in the boiling tube was refluxed with 10 c.c. benzene, filtered through the same Gooch filter, and washed with benzene until the runnings were colourless, after which the benzene extract was dried and weighed. Finally, the Gooch filter was also dried and weighed.

Test Results.

Effect of Temperature.—The first variable studied was that of temperature, the tests being carried out on a medium viscosity, solvent-treated mineral oil. This lubricant had a viscosity of 16·1 centistokes at 100° C., and a viscosity index of 95, indicating high paraffinicity. The effect of temperature on the loss due to evaporation after a uniform exposure time of 6 hr. is indicated in Fig. 5, in which the evaporation loss, expressed as a percentage of the original sample, is plotted against exposure temperature. The loss due to evaporation increased with temperature, but at a decreasing rate within the range studied.

Temperature had a marked effect on the formation of petroleum ether insolubles, or hard asphalt constituent, in the oil. It may be mentioned that, for the particular oil under review, no petroleum ether insolubles were formed at temperatures up to about 180° C. within the 6-hour test period, indicating only partial oxidation of the oil at these temperatures. At higher temperatures, however, petroleum ether insolubles were formed after exposure periods which varied with the test temperature. As a basis for comparison, the time to form 5 per cent. petroleum ether insolubles in the oil was determined over the temperature range 180–240° C. The results are shown in Fig. 6, in which the time to develop 5 per cent. petroleum ether insolubles is plotted against exposure temperature. The amount of the residue also varied with exposure time, as shown in Fig. 7, in which the percentage petroleum ether insolubles is plotted against exposure time for a number of temperatures. At the lower temperatures studied, the residue formed during the early period of exposure was completely soluble in benzene after treatment with petroleum ether, but with continued exposure the residue became only partly soluble in benzene, an increasing percentage remaining insoluble. With increasing temperature, the formation of insoluble residue occurred after shorter exposures. At the highest

temperature tried, an insoluble residue was formed almost from the commencement of the test.

The influence of exposure time and temperature on the strength of the oxidized film, as given by the force required to separate the dish and ring,

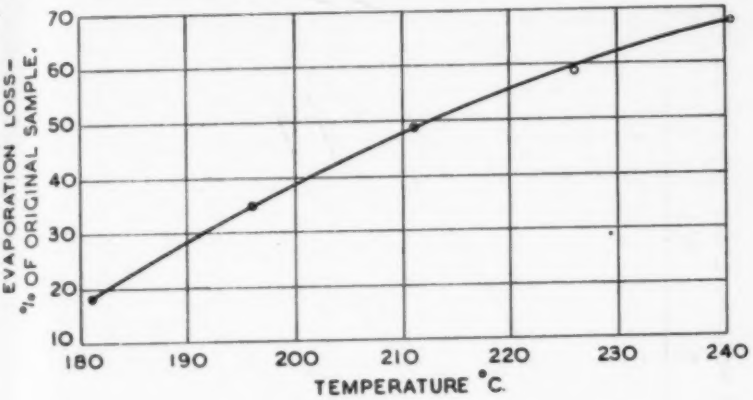

FIG. 5.

EFFECT OF TEMPERATURE ON EVAPORATION LOSS AFTER 6 HRS.' EXPOSURE.

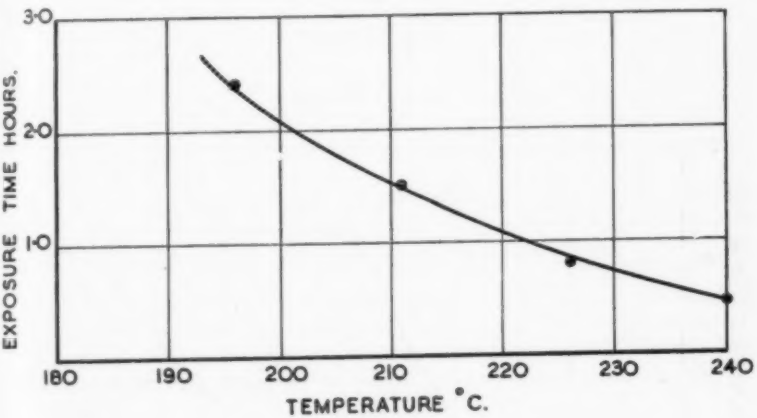

FIG. 6.

TIME TAKEN TO DEVELOP 5% PETROLEUM ETHER INSOLUBLES.

is shown in Fig. 8, in which the breakaway force is plotted against exposure time for a number of temperatures. In view of the small quantity of oil involved, the magnitude of the force required to separate the dish and ring appears unexpectedly high, but in subsequent tests on other oils a breakaway force as high as 65 lb. was recorded.

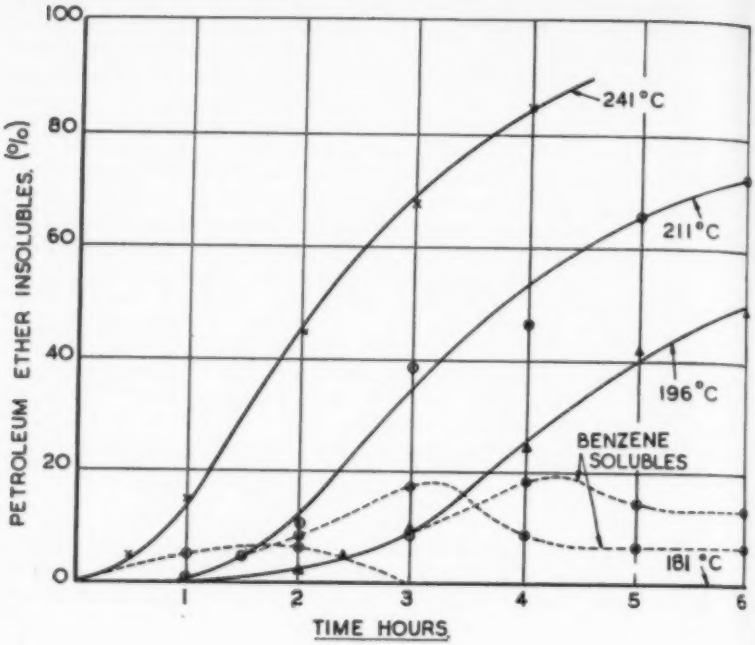
PETROLEUM ETHER INSOLUBLES. (%)
100
80
60
40
20
0
241°C
211°C
196°C
BENZENE SOLUBLES
181°C
1
2
3
4
5
6
TIME HOURS.

FIG. 7.

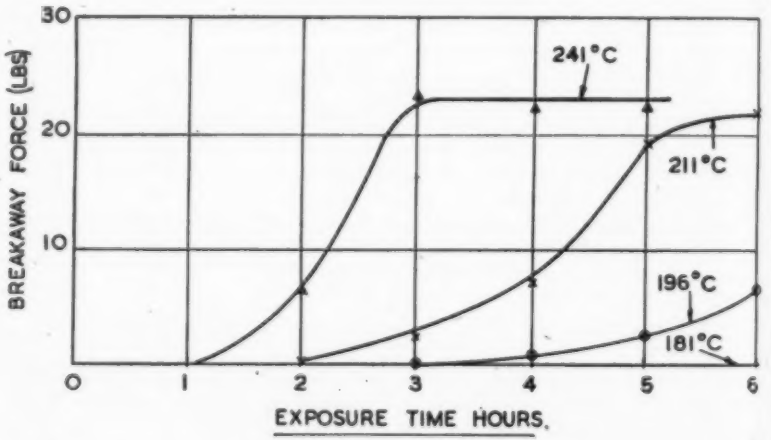
BREAKAWAY FORCE (LBS)
30
20
10
0
241°C
211°C
196°C
181°C
1
2
3
4
5
6
EXPOSURE TIME HOURS.

FIG. 8.

Some long period tests at 226° C. on four similar oils of different volatilities showed that the maximum breakaway force occurred with the oil giving the lowest evaporation loss.

Effect of Weight of Oil Sample.—The same size of dish and ring as in previous tests was used, but the weight of the oil sample was varied from 0·05 to 0·5 gm. The opportunity was also taken of investigating the effect of the initial oil viscosity. Samples of low-, medium-, and high-viscosity paraffinic engine-oils were tested at a temperature of 211° C., the exposure time being 4 hr. Data on these lubricants are given in Table I. In the present instance the low-viscosity oil was No. 18, the medium-viscosity oil No. 9, and the high-viscosity oil No. 1. The breakaway force is plotted in

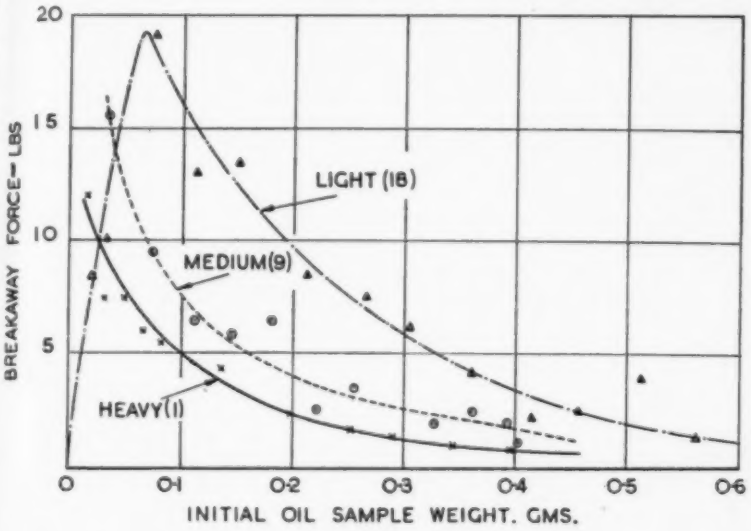

FIG. 9.

EFFECT OF OIL SAMPLE WEIGHT ON BREAKAWAY FORCE.

Fig. 9 against the initial oil sample weight. The greater gum-forming propensity of the lightest oil is clearly shown. In addition, within the range studied, the breakaway force increases with decreased sample weight—*i.e.*, with decreased film thickness.

TABLE I.

Oil No.	Type.	Viscosity.	
		Index.	At 100° C. Centistokes.
1	Aero Oil, a blend of synthetic oil and Penna Bright Stock.	111	21·0
9	Solvent-treated mineral oil.	95	16·1
18	Solvent-treated mineral oil.	99	8·3

Effect of Extended Periods of Exposure.—These tests were carried out on oil No. 9. Seventeen dishes were prepared containing the standard 0·25-gm. sample of oil and heated to 226° C. for periods up to about 90 hr. To cover the possibility of experimental variations in the results, several samples were examined at each interval of the test. The strength of the oxidized film was measured in each case. The results were erratic, and it is probable that, once having reached its maximum strength, the oxidized film becomes brittle or friable with continued exposure.

Correlation with Service Performance.

It will be appreciated that the foregoing describes an experimental technique giving results which may or may not bear any relation to service performance. In order to establish any correlation, it would obviously be necessary to undertake extensive engine tests under known conditions, together with a series of oxidation and gumming tests on the same lubricants at comparable test temperatures. It would then be possible to ascertain whether any correlation existed under appropriate test conditions, but such a correlation has not been undertaken in the present instance.

Some indication of the possible value of the test has, however, been obtained by the laboratory testing of a variety of lubricants which have been kindly submitted by certain oil companies, who have indicated, in many instances, the engine ring-sticking performance of the lubricants supplied.

One company submitted six petrol-engine lubricants which had been rated in air-cooled single-cylinder engines and also in full-size aero engines. The order of merit of these lubricants, as indicated by the breakaway force after exposure at 211° C., did not, however, agree very well with the order of merit under service conditions. It is possible that better correlation might exist at some other test temperature, and this possibility is now being examined.

It is of interest to note that the engine order of merit of these six lubricants agreed precisely with both the order of volatility and of chemical stability of the lubricants, determined as described above. Thus, engine ring-sticking increased with increasing volatility, the best oil showing an evaporation loss after 4 hr. of 24 per cent. and the worst oil a loss of 47 per cent., the others having intermediate values. The chemical stability was taken as the time to develop 5 per cent. petroleum ether insolubles, and in this respect, the lubricant most resistant to ring-sticking was rated at 3·8 hr., whilst the worst was rated at 1·4 hr., the others again having intermediate values.

In regard to lubricants for compression-ignition engines, a large number were submitted which had been tested under a variety of service conditions, but adequate particulars of these conditions were not supplied. It is therefore not possible to attempt, at this stage, any extensive correlation between engine and laboratory figures of merit, but the results indicate, in general, that lubricants which had been found to give low ring-sticking in service showed a maximum breakaway force ranging from 0·2 to 6 lb., the usual value being in the region of 4 lb. Such oils had relatively low viscosity indices, ranging from 28 to 60, and were asphaltic, Russian, or Gulf-type oils.

Oils which gave high ring-sticking on compression-ignition engines showed, on the other hand, a maximum breakaway force ranging from 3·6 lb. to 65 lb., most values exceeding 20 lb. Such oils were mostly of high viscosity index—*i.e.*, in the region of 80 to 110—and were essentially paraffinic.

Conclusion.

It will be appreciated that the simple test methods described in this report for evaluating the stability and ring-sticking propensities of lubricants are tentative in nature, and that a good deal of further experimental work will be necessary to indicate their precise value. It is considered, however, that the work so far accomplished may be of some interest to both petroleum technologist and automobile engineer.

OBITUARY

RICHARD VERNON WHEELER.

Dr. R. V. WHEELER, Professor of Fuel Technology in the University of Sheffield, died on 29th October, at the comparatively early age of 56.

He had been the occupant of the Chair of Fuel Technology at the above University for nearly twenty years, and simultaneously held the important post of Director of the research stations of the Safety in Mines Department.

Dr. Wheeler was educated at Owen's College, Manchester University, where he worked on the phenomena of combustion with the late Professor Bone. Later his researches on flame propagation were to win him an international reputation.

After some useful experience in industry, he took up his life work on combustion phenomena. He was intimately concerned with the stone dusting of pits and with colliery explosions. As a member of Government and trade Committees and as an advisor to Government Departments and industrial organizations, he made many contributions to safety in mines and to the application of scientific knowledge to industry. He was the first chemist appointed to the Explosion in Mines Committee of the Home Office, and was responsible for starting the work at the Home Office Experimental Station at Eskmeals, afterwards transferred to Buxton. In the domain of petroleum chemistry he did outstanding and pioneering work on the pyrolysis of hydrocarbons.

Prof. Wheeler was the author of many papers given before learned societies, and many members of the Institute of Petroleum will remember his paper on " Flame Characteristics of Pinking and Non-Pinking Fuels," read before the Institute in 1928. He was the editor of the well-known journal *Fuel in Science and Practice*, and wrote several monographs on his own subject. Of special interest is his work with Dr. Marie Stopes on the constitution of coal and its segregation into four chief classes.

Last year he was awarded the Melchett medal of the Institute of Fuel, and two years ago the gold medal of the Institute of Mining Engineers. He had been a member of the Institute of Petroleum since 1925.

His untimely death is a most serious loss to applied science and infinitely regrettable to his many friends.

A. E. DUNSTAN.